

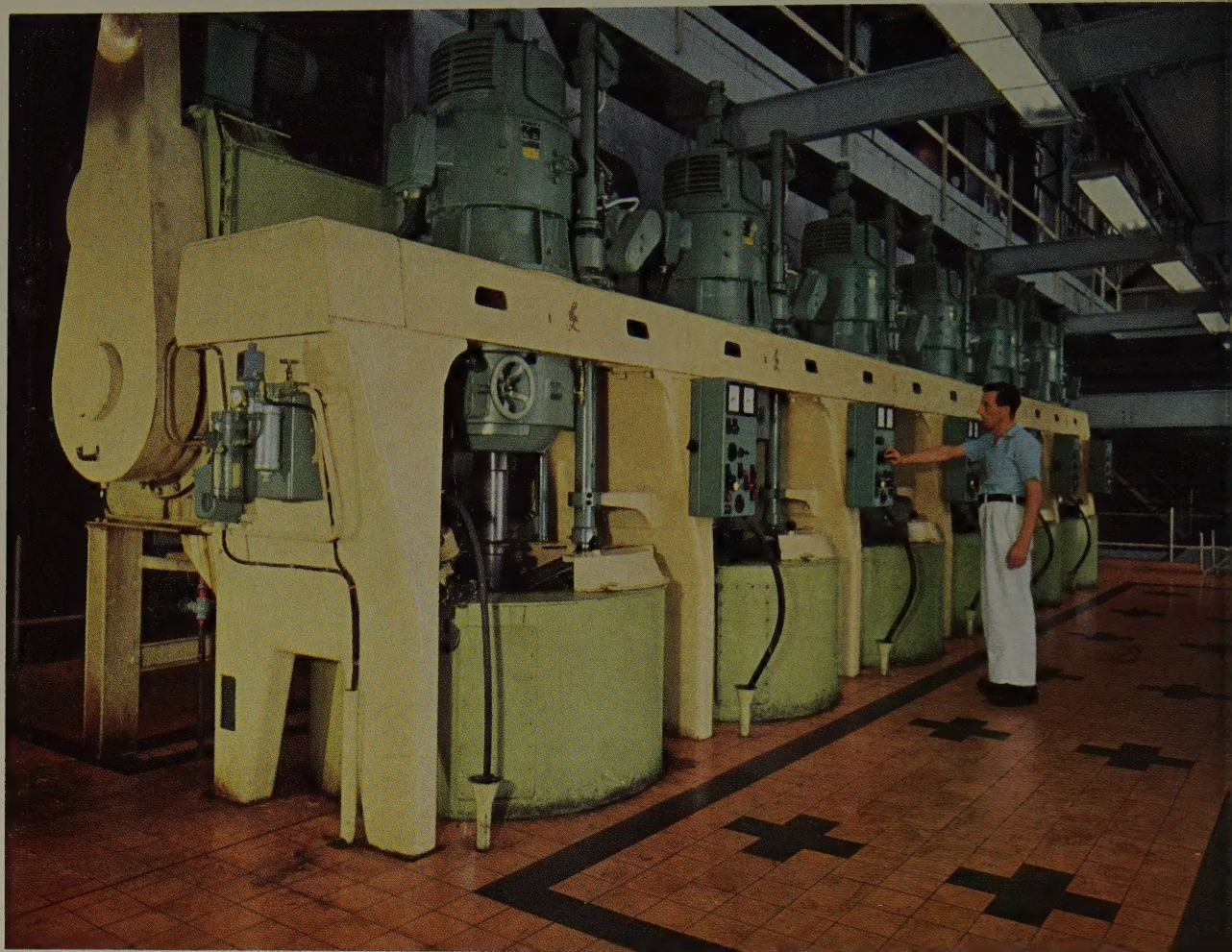


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1960

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THE STORNORRFORS TRANSFORMERS

or Sollergren, Transformer Department, Ludvika

U.D.C. 621.314.212
Asea Reg. 471

The Stornorrfor transformers, which form a three-phase group rated at 600 MVA, 18/400 kV, are the largest of the sixty-four 400 kV transformers so far manufactured by Asea. The design is described, with special attention to the ability of the transformers to withstand short circuits. Of the tests carried out, the impulse test is dealt with in greatest detail.

It was the case with transformers previously supplied to the Swedish 400 kV system, data for the Stornorrfor transformers could not be determined definitely by the Swedish State Power Board until the technical and economic aspects of a number of various alternatives had been investigated. The first alternatives examined had one feature in common, that is that there was to be transformation from the generator voltage up to both 130 kV and 400 kV, with auto-connected windings for these voltages. However, the 130 kV voltage was eventually discarded for certain technical reasons which need not be dealt with here. There then remained only one alternative, with direct transformation from the generator voltage to 400 kV only, which meant that, in principle, the transformers would be of simple design.

The total generator output of 600 MVA, supplied by four generators each rated at 150 MVA at 18 kV, made the use of two generator busbars necessary in order to limit the normal, and short-circuit, current on the generator side. Naturally, only single-phase transformers could be considered since the rating per unit would be 200 MVA and thus considerably greater than for the 400 kV double-wound transformers previously manufactured. To ensure that the distribution over two generator busbars would give the desired reduction in the maximum short-circuit currents occurring on the bars, each single-phase transformer had to be provided with two low-voltage windings with high reactance between the windings. This led to a basic solution for the transformers in accordance with Fig. 1. Thus, the high-voltage windings on the two limbs are connected in parallel, while the low-voltage windings are completely separate.

The final specification for the transformers contained, in addition to the general requirements of the Swedish State Power Board, the following prerequisites:

Insulation class for the 400 kV terminals	1500
Insulation class for the 400 kV neutral	375
Insulation class for the 18 kV windings	125
The lowest possible reactance between the 18 kV and the 400 kV windings, a desirable value being about 10 per cent.	

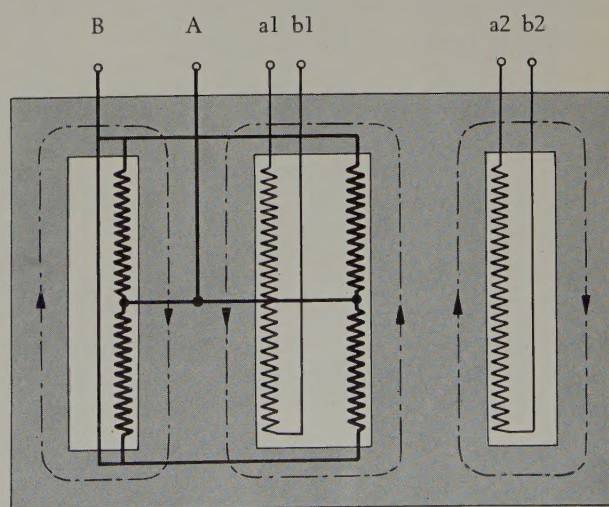
3. The transformers were to be able to operate continuously up to 10 per cent above the rated voltage.
4. The transformers were to be guaranteed to withstand the ultimate short-circuit power of 8,000 MVA from the 400 kV network and 3,000 MVA from each generator busbar.
5. The transformers were to be designed for direct cable connection on the 400 kV side. However, for voltage testing in the manufacturer's test department, the transformers had also to be provisionally fitted with normal 400 kV bushings.
6. The transport weight was not to exceed 180 tons.

THE DESIGN OF THE TRANSFORMERS

When the Stornorrfor transformers were designed (1955), the rating of 200 MVA per single-phase unit meant a considerable increase in relation to the Harsprånget transformers, which were designed for 115 MVA five years previously. The windings were, in this case, distributed over three limbs, that is, 38.3 MVA per limb, while the rating for the Stornorrfor transformers is 100 MVA per limb, or 2.6 times as great. The demand for low reactance was also the same. The problem could only be solved by taking yet another considerable step upwards in core size, and by using grain-oriented steel in the core. This material, which had previously not been used in cores approaching this size, made it possible in this case to increase the rating almost 20 per cent with-

Fig. 1. Diagram of the core and windings for a 200 MVA single-phase transformer. (Fr 855)

A, B The 400 kV winding
a1, b1 The one 18 kV winding
a2, b2 The other 18 kV winding



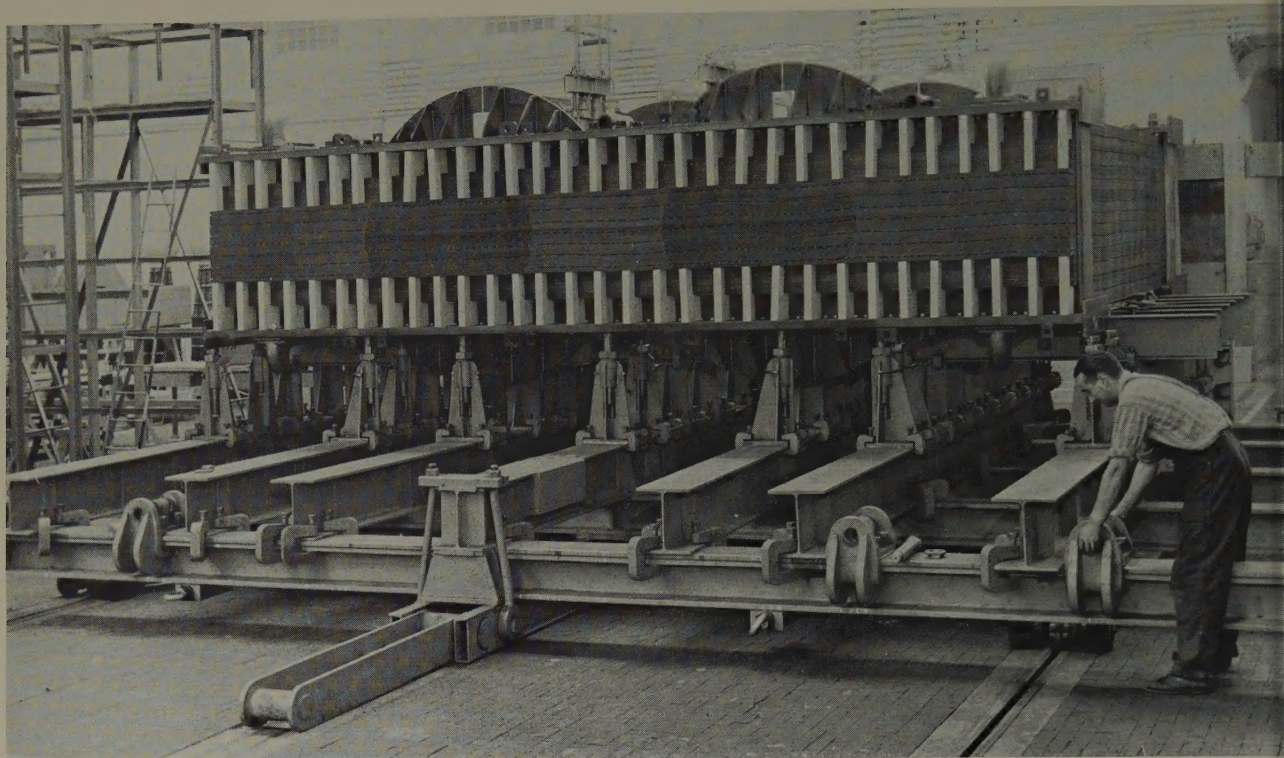


Fig. 2. The completed core on its assembly bed. (50056)

out increasing the reactance, as compared with designs using normal hot-rolled sheet steel with inferior magnetic properties. On the other hand, there was hardly any reason for using the expensive grain-oriented steel as far as the cost evaluation of the losses was concerned. The assessment of the losses when capitalised was relatively low: 1,500 kr/kW for no-load losses and 500 kr/kW for load losses.

Fig. 2 shows the core on the special assembly bed, and Fig. 3 shows the complete core with the yoke clamps in position, standing on the floor of the factory. The complete core, as shown in Fig. 3, weighs 128 tons. Before the windings were assembled on the cores, the latter were carefully tested to ascertain that the design values had been obtained.

The windings

The low-voltage windings, the rated current of which has the record value of 5,550 A, are designed as helical coils with a large number of parallel parts insulated from each other. In order to achieve an even distribution of current, the conductor parts are transposed in the normal way at regular intervals along the entire length of the winding. These windings are considerably larger and heavier than similar windings previously produced.

In principle, the high-voltage windings are designed in the same way as for all 400 kV transformers previously

manufactured. Thus, each limb winding consists of two winding sections connected in parallel, with the 400 kV terminal at the centre of the limb and the neutral at the yokes. The two limb windings are, in their turn, connected in parallel. The Stornorrfors transformers were among the first 400 kV transformers for which the insulation class was reduced from the original value of 1775 (for the years up to and including 1955) to 1500. However, this had no essential influence on the design of the winding insulation. Nevertheless, the most important insulation distances could be reduced in approximately this proportion, which was to some extent advantageous in order to fulfil the requirements for low reactance.

Fig. 4 shows one of the transformers complete with windings, cover, low-voltage bushings and the lower part of the high-voltage bushing. Fig. 5 shows the complete transformer with a normal 400 kV bushing, which, however, was only fitted in order to make testing possible in the manufacturer's test department. Fig. 10 shows two of the transformers erected in the power-station

Short-circuit strength

The designing of the windings with reference to the maximum short-circuit stresses under fault conditions will be dealt with in greater detail. In spite of the size and the high voltage, these transformers are, in principle, simple, since each limb has only two windings without any tappings at all. Significant axial amperes

n unbalance can therefore be avoided, and the axial symmetrical forces on the windings have consequently decisive influence on the design. It is therefore of particular interest to make numerical calculations of radial short-circuit forces, and the stresses caused them.

When calculating the short-circuit currents, it is convenient to regard the transformer as a three-winding circuit, using the equivalent diagram obtained from the short-circuit impedances. The diagram is made complete by including the impedances which have been calculated on the basis of the maximum short-circuit power values quoted, see Fig. 6, where the 400 kV winding is designated by the suffix 1 and the two 18 kV windings by the suffixes 2 and 3. When making the calculations, the impedance values of 11 per cent, measured between the 18 kV and the 400 kV windings, and 22 per cent, between the two 18 kV windings, were used. With the 400 kV winding as a base, the following impedances are obtained

$$Z_{13} = 0.11 \times \frac{400^2}{300} = 58.7 \text{ ohm/phase}$$

$$Z_{23} = 0.22 \times \frac{400^2}{300} = 117.4 \text{ ohm/phase}$$

Thus, the three-winding impedances calculated from this will be

$$Z_1 = 0$$

$$Z_2 = 58.7 \text{ ohm}$$

$$Z_3 = 58.7 \text{ ohm}$$

The short-circuit power values of 8,000 MVA and 3,000 MVA from the 400 kV network and each generator busbar give corresponding impedances

$$Z_{400} = \frac{400^2}{8,000} = 20 \text{ ohm/phase}$$

$$Z_g = \frac{400^2}{3,000} = 53.3 \text{ ohm/phase}$$

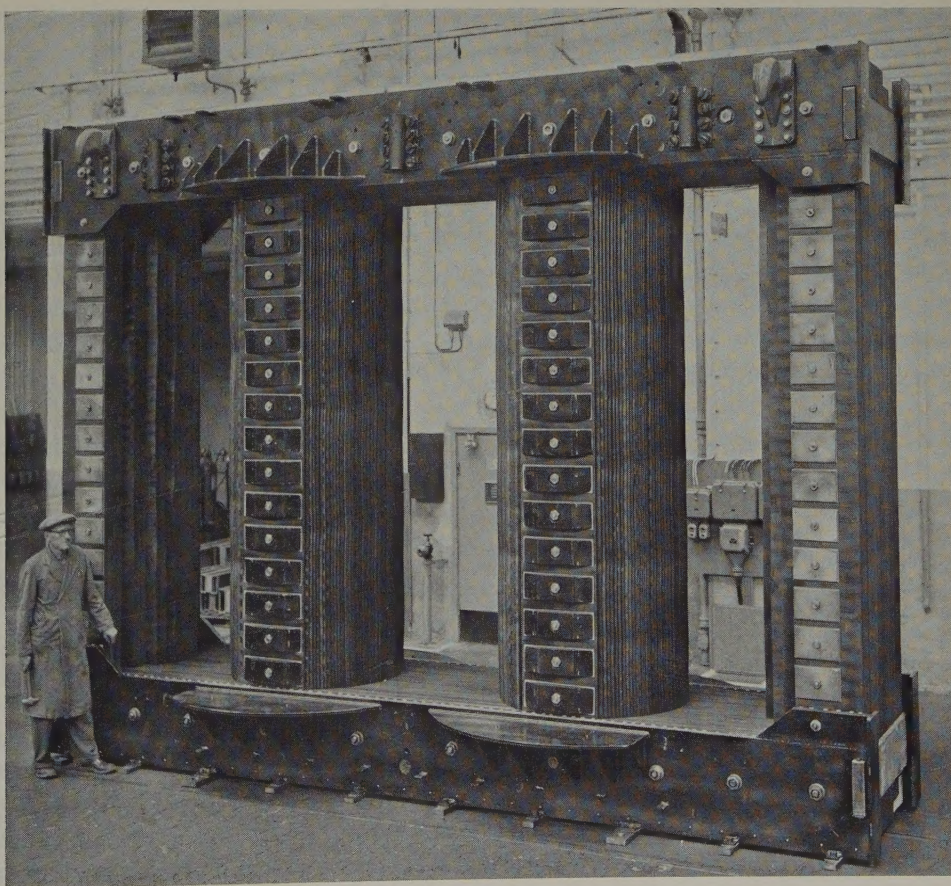
In the case of a three-phase short circuit on generator busbar 2 with the faulty point fed both from the 400 kV side and from generator busbar 1, the total short-circuit impedance Z_k for the calculation of the fault current i_3 will be

$$Z_k = 58.7 + \frac{20 \times 112}{132} = 75.7 \text{ ohm}$$

$$\therefore i_3 = \frac{400 \times 10^3}{\sqrt{3} \times 75.7} = 3,050 \text{ A}$$

Recalculated to the actual winding current in the 18 kV winding (D-connected).

Fig. 3. The complete core transformer being raised into the vertical position. Total weight 128 tons. (50057)



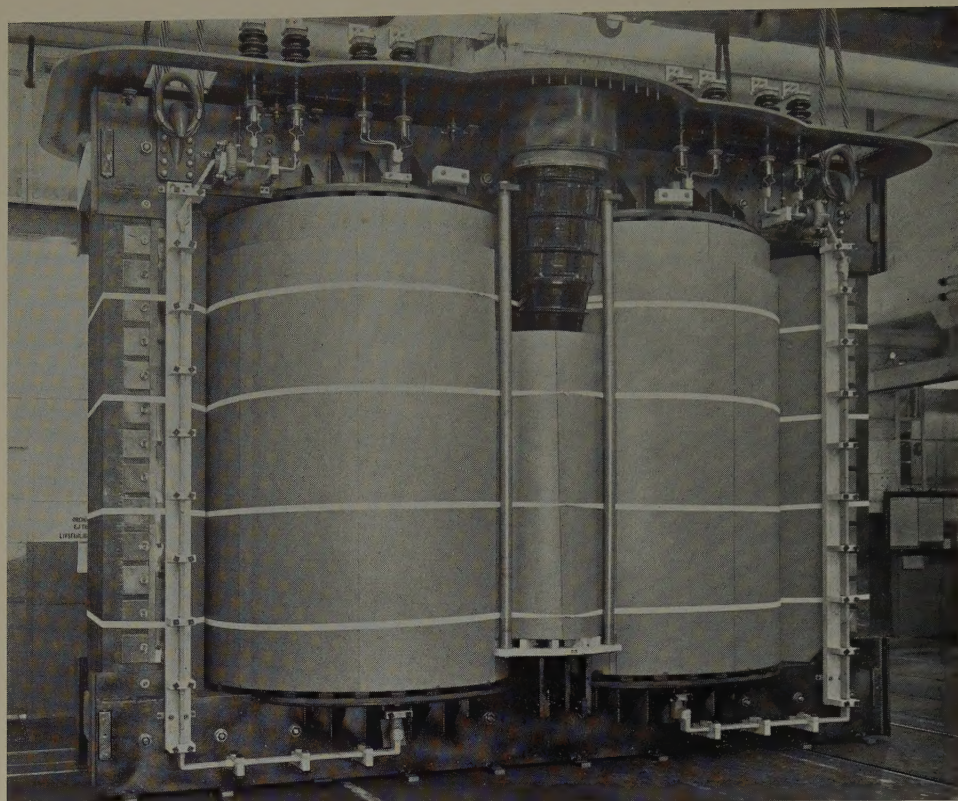


Fig. 4. Transformer with assembled windings. (50058)

$$i_3 (18 \text{ kV}) = 3,050 \times \frac{400}{\sqrt{3} \times 18} = 39,200 \text{ A}$$

(line current 67,700 A)

As will be seen from the diagram, the current $i_3 = 3,050 \text{ A}$ is the actual short-circuit current for the 400 kV winding on that limb on which the short circuit on the generator busbar occurs. The current $i_2 = 460 \text{ A}$ is the short-circuit current for the other 400 kV winding, and the line current on the 400 kV side is $i_1 = 2,590 \text{ A}$.

The radial current-forces cause tensile stresses in the outer winding and compression stresses on the inner winding. The maximum tensile stress σ to which the copper in the outer winding is subjected can be calculated in accordance with the following formula [1]

$$\sigma = 1.4 \times \frac{S_k^2 \times G_k}{H} \text{ kg/cm}^2$$

where

S_k = current density in A/mm², based on the R.M.S. value of the short-circuit current

Note. The unsymmetrical current peak on which the calculation of the stresses is based has been assumed to be 2.5 times the R.M.S. value of the current.

H = the axial height of the winding, in metres

G_k = the weight of copper per winding, in metric tons

The maximum short-circuit currents as calculated above are seven times the rated current. The current density

at rated current is 3.1 A/mm² and S_k in the formula therefore becomes 21.7 A/mm², an apparently relatively modest value. However, inserted in the above formula with the actual value of G_k/H , it gives $\sigma \approx 1,000 \text{ kg/cm}^2$ which is the maximum stress which Asea permits for copper which has not, before winding, been subjected to special cold working treatment, which increases the yield strength of the copper.

At the time when the tender was submitted, experience with specially treated winding copper was somewhat limited. Since the units involved here were very large there could be no question of taking any risks when short-circuit forces were concerned. Therefore, stresses higher than those previously permitted for large power transformers were not accepted. In fact, only those values which could be verified as being permissible as a result of short-circuit tests to destruction on the large transformers which can be tested in the Asea High power Laboratory were accepted.

Extremely valuable experience has been derived from short-circuit tests of this kind, which, during recent years, have been carried out on a large scale. However, it must be borne in mind that even the largest experimental transformers which can be tested in the very largest modern high-power laboratories cannot be regarded as being more than models with a power of only about a tenth of the Stornorrfor's transformers. Naturally, to adapt the results obtained by model testing to scale ten times larger is difficult, but without the suppo-

similar tests, the designing of extremely large transformers would, however, be a more or less hopeless task.

It should be particularly noted that no practical experience in service can be drawn upon in order to judge the short-circuit strength of large transformers. Line short-circuit power is increasing steadily, and it is for the maximum power values, which will not be achieved until some time in the more or less distant future, that the transformers have to be designed. Bearing in mind, however, that short circuits are relatively rare, satisfactory experience in the past cannot be quoted as providing any guarantee that large power-transformers will function equally well in the future.

It will be seen from the above that the short-circuit strength has been of decisive importance when designing the windings. The cost evaluation of the load losses was exceptionally low that, from this point of view, higher current densities would have been economically justified. By this means, it would also have been possible to reduce the impedance to somewhat less than 10 per cent, which the customer would have considered to have been extremely advantageous if the same guarantees concerning the short-circuit strength could have been given.

Thus, the decisive factor is the ability of the transformer to withstand short circuits in a future network, in spite of the fact that this cannot be verified by any tests and cannot be checked on the basis of calculations worked out using any generally accepted formulae. This is, unfortunately, not a condition which applies to the very largest transformers alone, since it also applies to most large power-transformers.

Short-circuit strength has now become more or less a question of confidence between the customer and the manufacturer. As has previously been pointed out in the Asea Journal [2], no foreign standards have recognised the difficulties concerning short-circuit guarantees. However, an attempt is being made to introduce a change into the I.E.C. standards (I.E.C. Publication 56) which are now being revised.

In the manufacturing processes to which the windings are subjected in order to obtain the greatest possible short-circuit strength will also be dealt with briefly. Expressed in simple terms, the final object of all winding treatment is that the windings should be firmly compressed when new, and no shrinkage should be allowed to take place, even after many years of service. Radially, all coils should also have the greatest possible stability which it is possible to achieve in production.

In principle, all this is ensured by a series of drying, pressing and impregnating processes, by means of which the windings and the end insulation take on the exact shape required. Experience has proved that it is possible to obtain windings which remain permanently braced

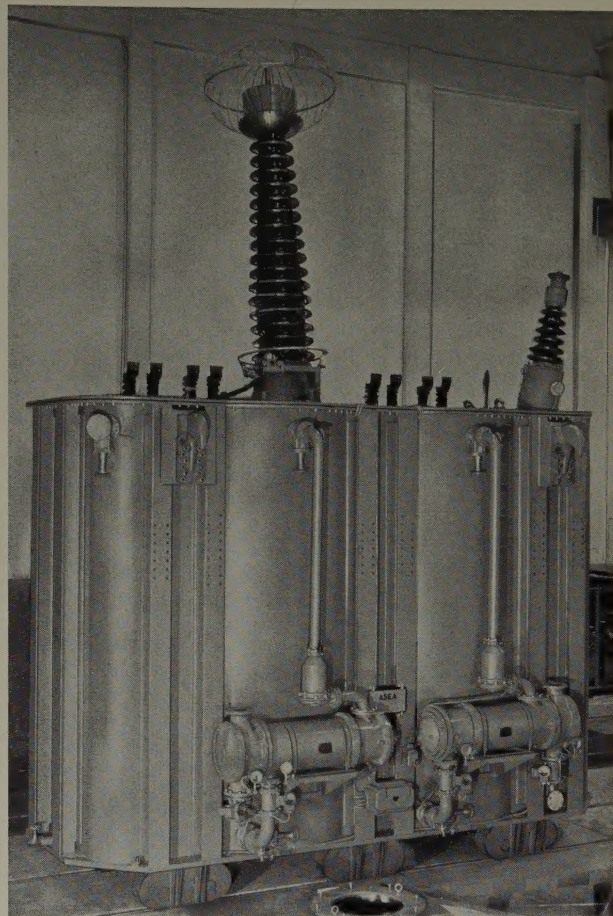


Fig. 5. Single-phase transformer for Stornorrfor for 100/100/200 MVA, 18/18/ $\frac{400}{\sqrt{3}}$ kV, forced-oil-cooled, with two built-on oil coolers. (50060)

between the yokes. This has been possible by applying pressure of suitable values to the windings at least as great as that expected to arise from the short-circuit forces. Further, the final assembly of the windings on the core has been carried out with the windings held down by hydraulic jacks to facilitate the blading in of the top yoke.

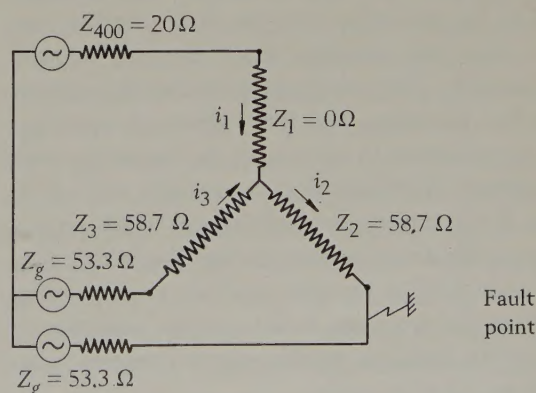
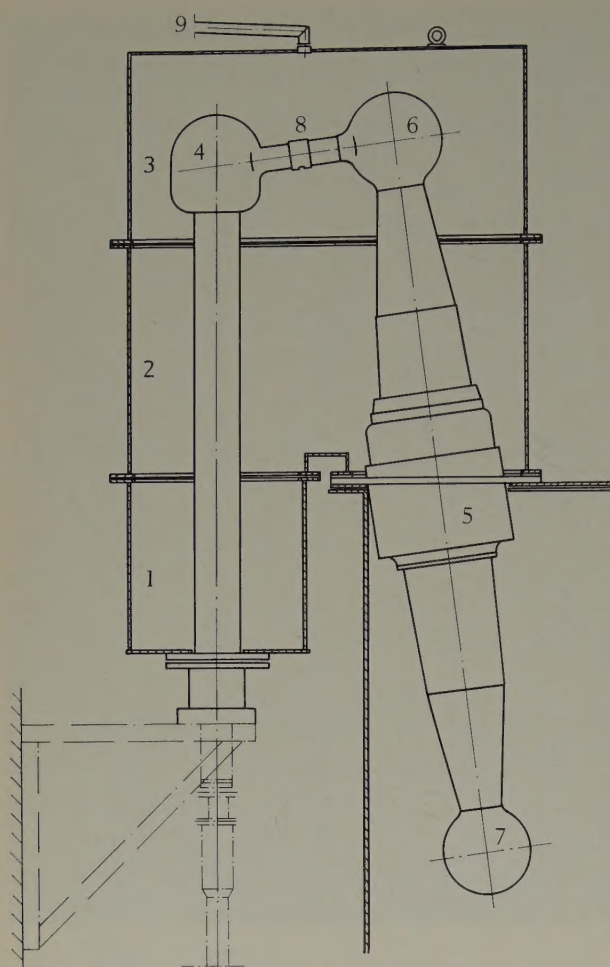


Fig. 6. Equivalent diagram for the calculation of short-circuit currents. (Fr 856)



- 1-3 Sheet-steel housing in three parts
- 4 Paper-insulated sphere
- 5 Transformer bushing
- 6, 7 Spherical electrodes
- 8 Screening tube in two pieces
- 9 Pipe

Fig. 7. Elementary sketch of the 400 kV cable box. (Fr 857)

This is by no means a simple matter since the windings contain a relatively large amount of insulating material such as paper and presspahn. The compressibility of the winding depends to a very great extent on the moisture content of the insulating material. It is therefore not sufficient that the windings should be well clamped during assembly. The windings must also be perfectly dried before mounting, and they cannot be permitted to take up moisture to any extent in connection with this operation. Naturally, this is especially difficult in the case of the very largest transformers which require a longer period of time to pass through the factory than smaller units do. The time the windings are exposed to the ambient air, from the final treatment until the assembly of the windings on the core is complete, must be made as short as possible. The maximum time permitted depends on the moisture content of the ambient air.

One of the reasons which has contributed to a satisfactory result is, significantly enough, the fact that the works are situated in a district where the climate is relatively dry. However, since the weather conditions cannot be relied upon entirely, it has proved expedient to have a special dry room available (relative humidity as low as 5 per cent). Here the windings are stored from the time when the treatment is completed until they are required for assembly on the core. This applies unless the period of waiting is shorter than a day or two, which is not, however, the case with large multi-winding transformers.

Without the advantage of a particularly favourable climate and the air-conditioned storage room, the method briefly sketched out above of preparing windings which remain permanently braced would hardly have proved successful. The only alternative would have been to have used an adjustable coil-clamping device. However, in our opinion, this method has serious disadvantages.

The 400 kV cable connection

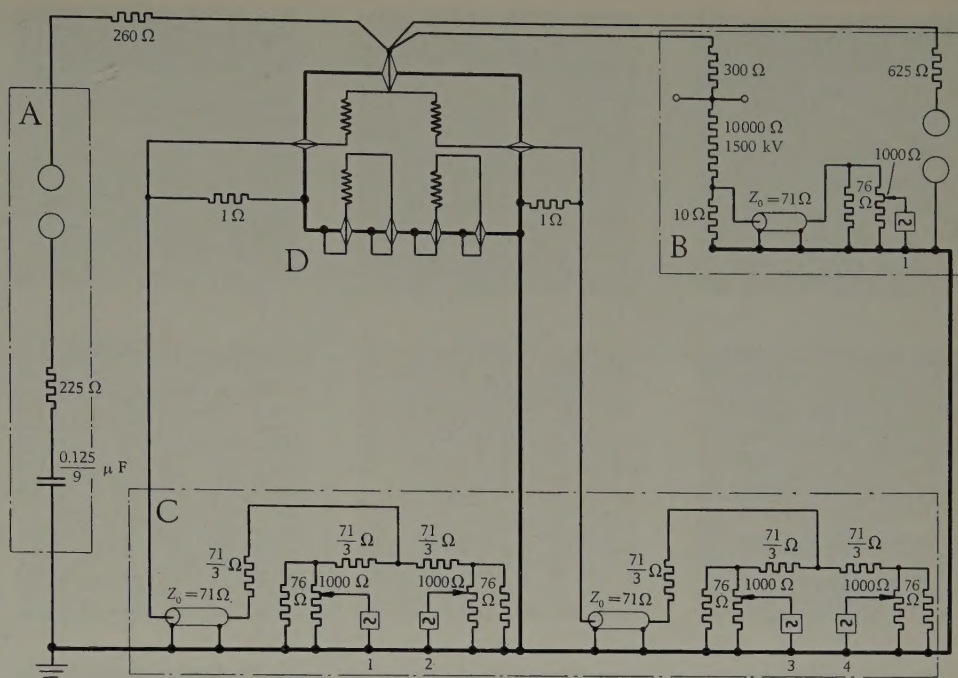
Fig. 7 shows, in principle, the arrangement of the 400 kV cable box and demonstrates how it is combined with the transformer. The cable enters from below and extends into a sheet-steel housing 1-3 which is divided into three parts. The cable terminates in a paper-insulated sphere 4. The transformer bushing 5, the lower part of which can be seen in Fig. 4, has spherical electrodes 6 and 7 at the top and bottom, and these are similarly insulated with paper. The bushing, the total length of which is about 5 m including the spheres, is of condenser type with the condenser body made of oil-impregnated paper. The electrical connection between the bushing and the cable consists of flexible cable between the spheres 6 and 4. The conductor is surrounded by a screening tube 8, in two pieces, with the joint insulated with paper. The cable box is connected by means of the pipe 9 to a separate oil conservator with a gas-operated relay in the connection pipe. The completely enclosed condenser bushing is also connected to the same oil conservator by means of a pipe from the central flange and provided with a gas-operated relay (not shown in the figure). However, this latter relay cannot function for slow formation of gas in the bushing. It is only actuated by major faults which cause a rise in pressure and with it an adequately powerful flow of oil. In addition to the gas-operated relay protection, a signalling thermometer is connected to the upper part of the sheet-steel cover

THE CUSTOMER ACCEPTANCE TESTS MADE

All the four single-phase transformers included in the delivery for Stornorrfor were subjected to identical tests as described below:

Impulse generator
Voltage measurement
1. Voltage oscillograph
Current measurement
1, 2, 3, 4. Current
oscillographs
Transformer being tested

Fig. 8. Elementary diagram
of impulse tests on 400 kV
transformer with two separate
400 kV individual
windings. (Fr 858)



Measurement of the resistance in the windings, ratio tests, etc.

No-load and short-circuit tests to determine losses and short-circuit voltages.

Impulse tests on the 400 kV winding with three full impulses with the wave form 1/50 in accordance with Swedish Standard SEN 26, and an amplitude of 1,500 kV (deviation from the standard wave shape, see below).

Induced voltage test with increased frequency with an R.M.S. value of 660 kV to earth on the 400 kV side. In order to check the neutral-point insulation, the 400 kV winding was also tested with 165 kV, 50 c/s, for one minute. The 18 kV windings were tested in the same way with 55 kV.

Because the power required considerably exceeds the resources of the test department, no temperature tests could be carried out. In accordance with the agreement with the Swedish State Power Board, temperature tests were however to be carried out at Stornorrfor, but it has not yet been possible to do this. However, even without temperature tests, it can be assumed that the temperature guarantees will be kept with some margin. The total losses of the transformers at rated power are about 800 kW. The two oil coolers with a combined cooling effect of 900 kW have been built to give an average temperature rise in the oil of max. 30°C, and the temperature gradient between the average temperature rise of the oil and that of the winding is also calculated to be less than 30°C. This should thus result in an average temperature rise for the windings which is below the guaranteed value of 60°C. The increase in temperature mentioned will be above the tempera-

ture of the cooling water, which, in accordance with the standard, is assumed to have a maximum of 25°C. Naturally, the actual value is considerably lower. The nominal quantity of oil per cooler is 1,000 l/min (220 gal/min), and the quantity of water 1,080 l/min (237 gal/min). The pressure drop is 11.5 lb/sq.in. on the oil side and 3.4 lb/sq.in. on the water side. The transformers are fitted with two temperature indicators which, on the basis of temperature tests carried out, can be set so that they show the approximate hot-spot temperature of the two low-voltage windings.

An account of the impulse tests

For the impulse tests, use was made of the High-voltage Laboratory's largest impulse generator which has 9 stages each with a capacitance of 0.125 μF. The connection diagram for the tests can be seen in Fig. 8. Since the 400 kV winding consists of two separate windings, it is particularly desirable to be able to take oscillograms of the currents in each winding separately, so that, if a fault occurs, it is possible to determine which winding failed. This problem was solved in the same way as for those 400 kV transformers with two, or even three, windings, which had been tested previously. Thus, during the tests, the neutral ends of the individual limb windings were not connected together, but had separate terminals. The currents were registered with two current oscillographs per winding, the one working with a relatively short time sweep of 40 μs, the other with a longer sweep of 250 μs. The time sweep had a logarithmic time axis. Oscillograms were taken of the voltage by means of a shielded resistor voltage-divider. The oscillograph had a zig-zag sweep with a linear sweep time of 5 μs.

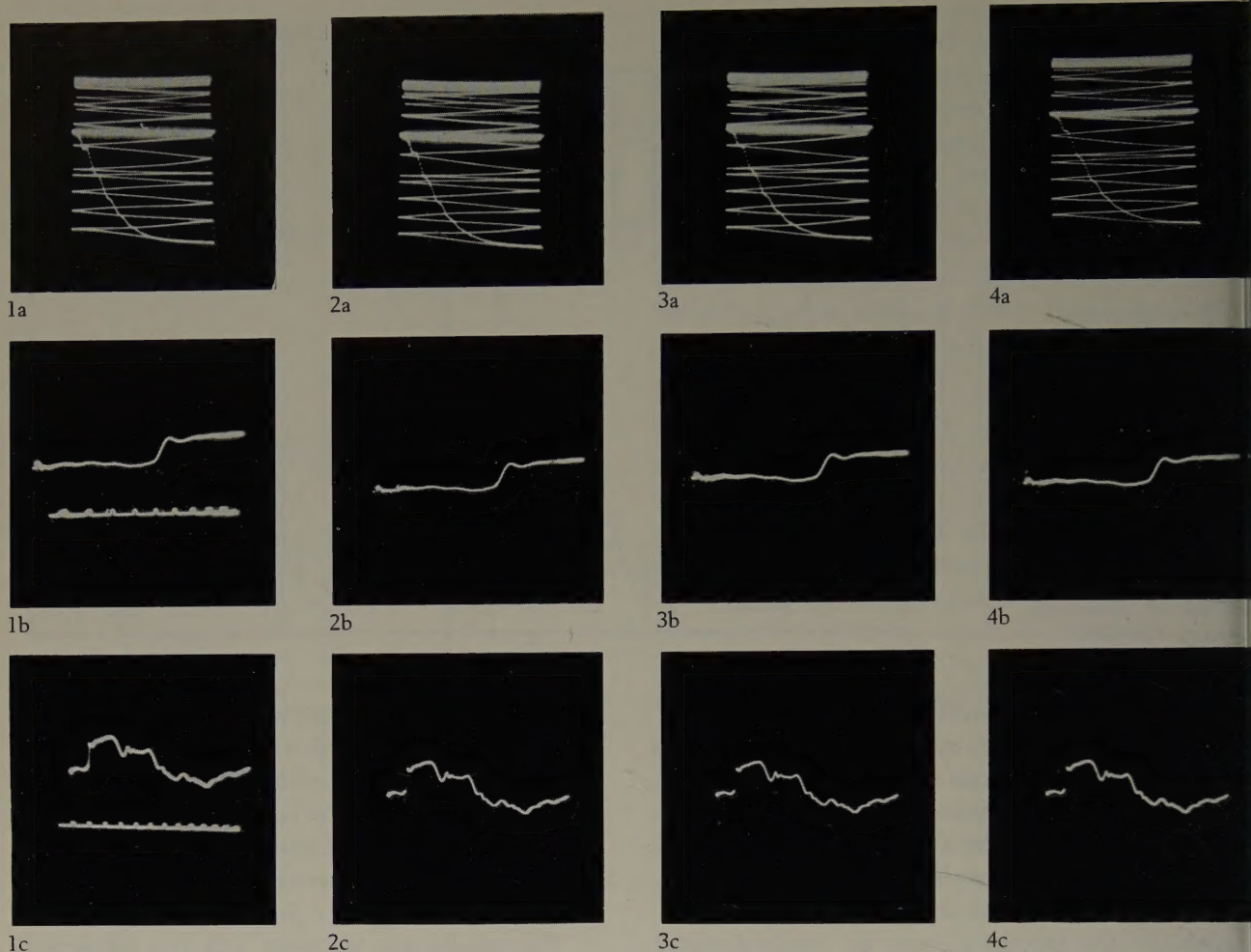


Fig. 9. Voltage, and current, oscillograms for impulse tests on one of the 400 kV windings. 1a, 1b and 1c calibration oscillograms at 900 kV. 2a, 2b and 2c corresponding oscillograms for the first impulse of 1,500 kV. The same applies to oscillograms 3 and 4 for the following two 1,500 kV impulses. (Z 10786)

The tests on all four transformers were completed without any indications of faults in any of the windings. Fig. 9 shows the voltage, and current, oscillograms for one of the windings in a transformer. According to the voltage oscillogram, the actual wave-shape is approximately 2.5/30 instead of the desired 1/50. A front-time as short as 1 μ s is generally impossible to achieve for transformers of this kind (the American Standards permit a front-time of 3 μ s for insulation classes above 650 kV). The difference between 30 μ s and 50 μ s in the time to half-value may be regarded as being more or less insignificant because of the time-curve characteristic for oil-paper insulation. Finally, as far as the oscillograms are concerned, they show exact correspondence down to the smallest detail at 900 kV and 1,500 kV for both time sweeps, which is conclusive evidence that the transformers withstood the impulse test without any faults occurring.

After the impulse tests, the induced voltage test was carried out at 660 kV, with completely satisfactory results for all the four transformers.

CONCLUSION

The delivery of the Stornorrfor's transformers was concluded from the factory in February, 1958. Erection of the station was completed in September the same year and everything went according to plan, without any major difficulties. Both as far as transport weight (18 tons) and total weight (224 tons) are concerned, the units are rather heavier than the largest 400 kV transformers previously supplied. However, the difference is not very great. As far as the rating is concerned, a fair comparison can only be made with transformers stepping up from generator voltage to 380–400 kV. Transformers of this kind have not been made after the units for the Harsprånget and Ligga Power-stations, which are both considerably smaller (115 MVA single-phase, and 100 MVA three-phase, units, respectively). A comparison with the largest auto-connected grid transformers hitherto supplied, of which some are also designed for simultaneous stepping up from generator voltage,



Fig. 10. Two of the transformers erected in the power-station. (3338. Photo Ekholtz)

most impossible. Of these, the transformers for Hallsberg, which are being commissioned in April, 1960, and have a power of 1,000 MVA for a single three-phase group, are the largest made hitherto. However, from the point of view of weight, they are only 10 per cent heavier than the transformers for Stornorrfor.

Further technical developments will be determined entirely by future needs. However, if even greater units are

required in the future, resources are already in existence for their design and manufacture.

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LARGE ARC FURNACES FOR STEELWORKS

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U.C.D. 669.187
Asea Reg. 663

Translation of an article in Teknisk Tidskrift 89 (1959): 29, pp. 721-727

The article compares various arc-furnace designs, with particular reference to bucket charging, tilting devices, cradles and rails, the furnace shell, roof rings, doors, electrodes, electrical equipment and fume extraction.

It is now rather more than 50 years since the first arc furnaces started to come into use in the steel industry. To begin with, these furnaces were quite small. The power input amounted to a few hundred kVA, but it is interesting to note that, even so, this relatively moderate power consumption caused considerable difficulties as far as the supply network was concerned. To begin with, the furnaces were built in many shapes, but it was not long before the main features stabilised themselves, the furnaces taking on the shape that they have retained to the present day, namely a circular furnace shell with three vertical electrodes passing through a roof.

The arc furnaces are now not only used for alloy steels and other high-quality steels, but they have started to

be used throughout the world, and in Sweden too, for the manufacture of simpler types of steel such as plain carbon steel. In Sweden 70-90-ton furnaces with transformer outputs of 20-25 MVA have recently been installed. On the continent of Europe 150-ton furnaces with a transformer output of 36 MVA are in use, and in the U.S.A. the development is on the point of going even further. There 250-ton furnaces are under discussion.

A modern arc furnace with considerable transformer capacity represents a major capital investment. The sum involved is of the order of size of 100-150 Sw. Kr./kVA (or 7-10 £) of installed electrical power. Naturally, it is important in the first place to utilise an installation of this kind as effectively as possible, that is to say, the ratio between the mean load and the maximum installed power should be as great as possible. In other words: the utilisation factor should be high.

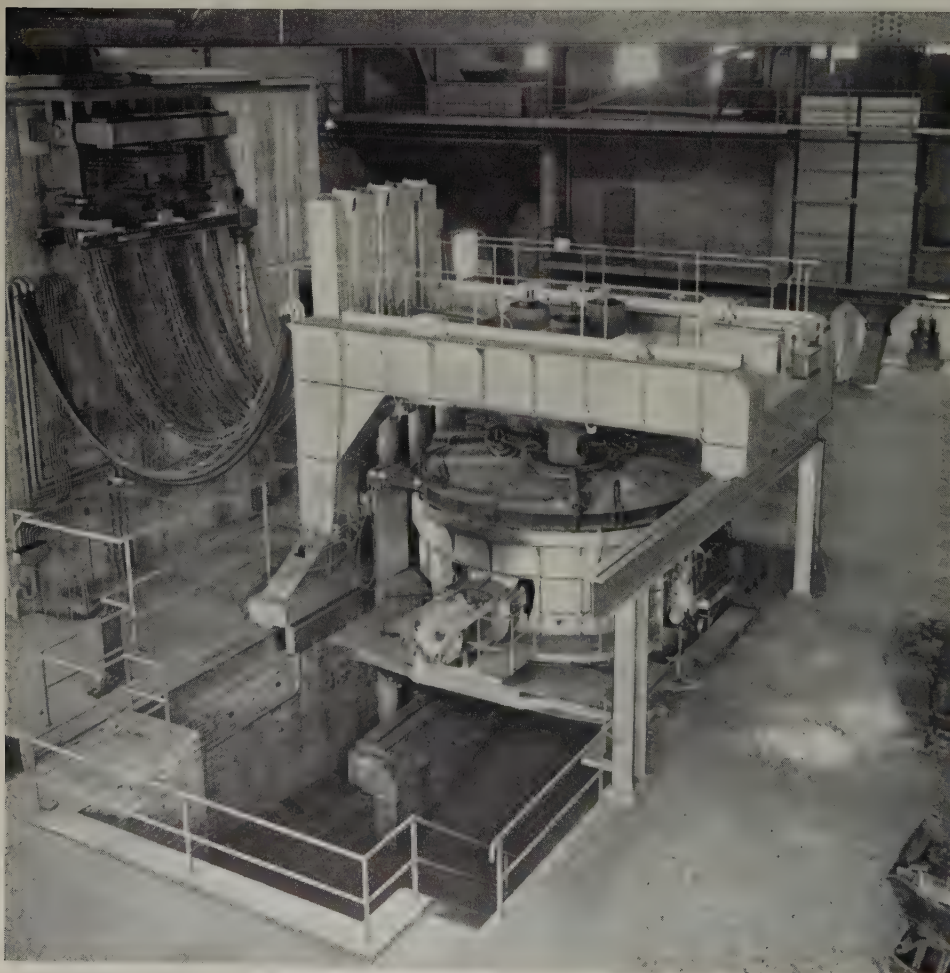


Fig. 1. Arc furnace of gantry type; furnace shell diameter 5 m (about 16 ft 6 in.), charge 40-50 tons. (45737)

the most important feature in the development of the arc furnaces during recent decades, apart from the growth in furnace size, is the series of improvements which has led to the attainment of a high utilisation factor. To attain this, an attempt has been made to achieve a high degree of mechanisation of all the processes incorporated in the operation of the furnace. These attempts have culminated in a reduction in the charging time, and since most of the losses connected with the furnace are those which are directly proportional to the time involved, a reduction in the time required for the various component operations in the charging procedure means an increase in the total efficiency of the furnace. This is an important feature to bear in mind when attempting to increase the efficiency of the furnace.

BUCKET CHARGING

Modern arc furnaces are, almost without exception, intended for the melting of considerable quantities of scrap, and therefore they are almost always designed for bucket charging. In principle this type of charging can be arranged in three different ways.

The first way is to place the furnace shell itself on wheels running on rails set in a foundation, so that the shell can be rolled free of the other parts of the furnace. In this way it is possible to charge the furnace from above, after which operation it is moved back into its original position. This design, however, has two considerable and basic disadvantages. The first is that it is expensive and the second that it is fairly complicated and can therefore give rise to difficulties during service and maintenance, service conditions in the case of arc furnaces being extremely severe. Further, a travelling shell requires a complicated working platform and makes difficult the possible later installation of an induction stirrer beneath the furnace.

The second design principle (Fig. 1) is represented by the gantry crane. Here the roof and the electrode system, etc., are supported by a gantry crane which can be moved to the side on wheels thus opening up access to the furnace. The gantry can be made with a single leg, being supported on the other side by wheels on an overhead track above the charging level so that the furnace is accessible from this latter side.

Usually the gantry is so made that it takes part in the tilting movement of the furnace. There are, however, certain advantages connected with a non-tilting gantry, for example, short flexible cables, simple tilting machinery and an extremely short tapping spout. The electrodes always remain vertical, which is advantageous in,

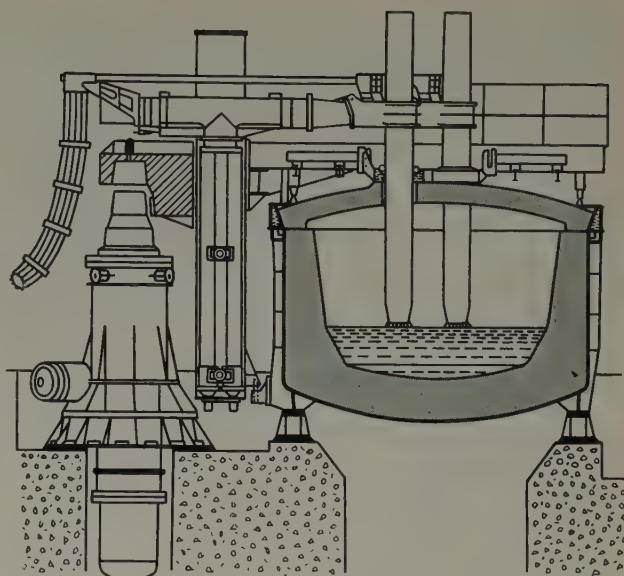


Fig. 2. Arc furnace of swing-roof type with separate ram. (Fr 1134)

for example, the case of Söderberg electrodes. It is, however, a disadvantage when it is a question of tilting the furnace a few degrees for deslagging without withdrawing the electrodes. The roof then takes up a position at an angle to the electrodes thus complicating the design of the electrode glands.

In recent years gantry-type furnaces have been neglected in favour of swing-roof furnaces, which is regrettable in that the gantry-type furnace design is simple and effective and is in no way more expensive than the swing-roof design. The gantry type is particularly suitable for furnaces installed at tapping bay level, in other words, those having a pouring pit.

The third method for the bucket charging furnace is the swing-roof principle. There are four design variants within this group. The first system, which is the one most used in the U.S.A., has a ram mounted on its own separate foundation, around which the roof and the electrode system swing (Fig. 2). This ram is hydraulically operated so that it can raise itself and lift the entire electrode system with its roof, thus freeing the roof from the shell and allowing the entire upper part to swing to the side.

This system has the advantage that the furnace shell is mechanically quite free of the roof suspension device when the furnace is charged, thus avoiding all risks of vibrations and shocks, which may arise during bucket charging, affecting the roof. The problem of the centre of gravity is also simplified when swinging takes place since the swinging part has its own support.

Disadvantages are the expense and the difficulty of having a separate foundation for the ram. This founda-

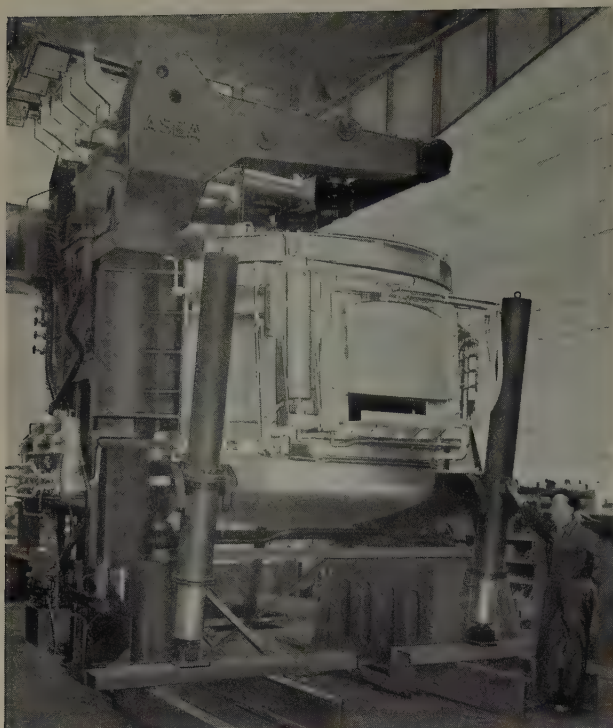


Fig. 3. Furnace of swing-roof type with the swinging column mounted on the furnace shell; diameter of the furnace shell 2.5 m (about 8 ft), charge 3-5 tons. (48621)

dation simply cannot be allowed to move in relation to the furnace foundation. Another disadvantage is the relatively long distance from the central pivoting point of the ram to the centre of the furnace. Finally, it is difficult to arrange a rotatable furnace shell since, during operation and tilting, the furnace shell forms the support for the entire upper part. It is interesting to note in this connection that the advantages of having a rotatable furnace shell do not appear to have been observed in the U.S.A.

The second design principle for the bucket charging type of furnace is also of American origin. The swing-roof column is fastened to the furnace shell (Fig. 3). The main disadvantage of this design is that shocks which arise during charging may transfer themselves directly to the suspended roof. Further, a mechanical arrangement in which the furnace shell itself has to support such a large and heavy device as the entire electrode system with its swinging superstructure and roof, must be regarded with a certain amount of suspicion in the case of large furnaces. For small furnaces, however, experience has shown that the design is very satisfactory. Of course, it is not possible to rotate the furnace shell in this design.

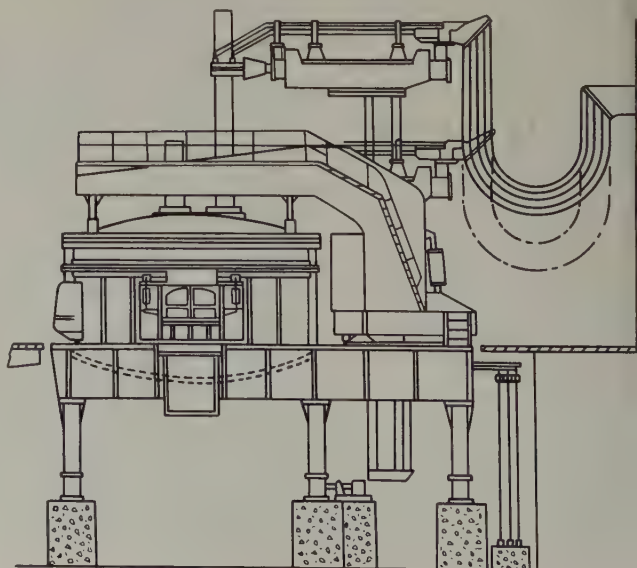
In the third type, the furnace shell is placed on a framework (Fig. 4). The latter also carries the entire superstructure and electrode system which can be swung to the side, and which runs in a circular track like a roundabout. A disadvantage is that there is a considerable

distance between the pivoting centre of the superstructure and the centre of the furnace, because of the fact that the circular "roundabout" track has to run between the swinging structure and furnace shell. In the case of larger furnaces, this results in the need to provide a third supporting cradle to prevent the furnace from toppling over when the roof is swung out. Further, if electrode cylinders are fitted they cannot be permitted to project beneath the framework since they would then get in the way of part of this framework when swinging out. This necessitates a gearing up of the electrode movement thus enabling shorter cylinders to be used.

The fourth design principle is similar to the last-mentioned one. A swing column is placed on a framework around which the swinging superstructure rotates (Fig. 5). There is, however, no "roundabout" track, but instead use is made of a design similar to that for the gun turrets on warships or for slewing cranes on ships.

By this means a very compact design is obtained, and by placing one of the electrode masts with its appropriate hydraulic cylinder in the centre of this swinging turret a considerable reduction in breadth is obtained. This is advantageous from the point of view of the building since it is always necessary to fit the furnace in between two of the columns for the overhead crane tracks. Another advantage of the design is the short distance between the swinging centre and the centre of the furnace, thus enabling short electrode arms to be adopted which, in the case of large furnaces with heavy electrodes, is of vital importance. It is easy to arrange rotation of the furnace shell, and the electrode cylinders do not have to be shortened in any way.

Fig. 4. A 120-ton arc furnace of swing-roof type with a circular track. (Fr 1135)



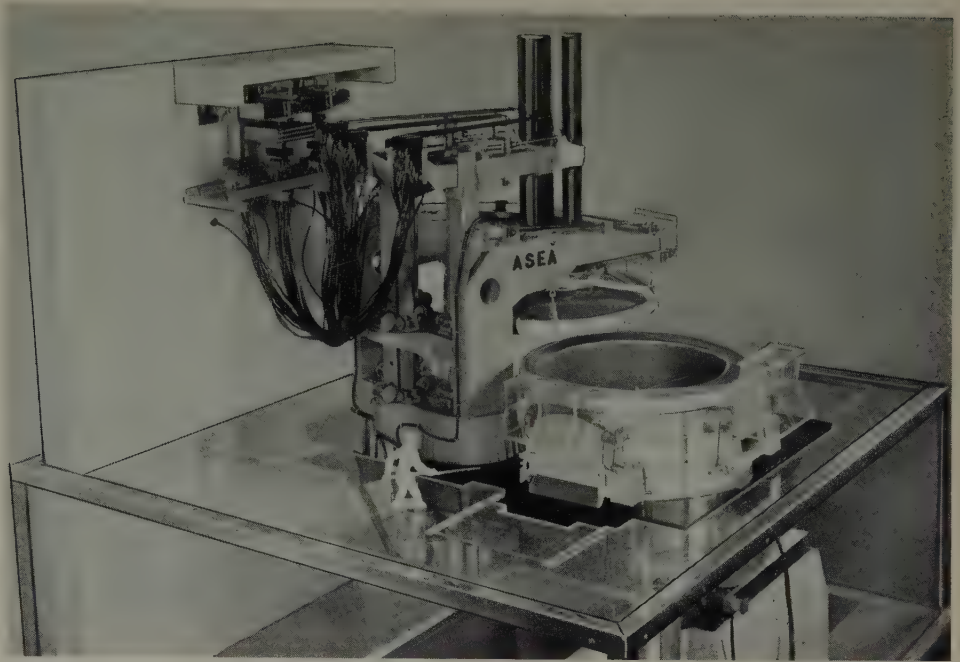


Fig. 5. Model of a swing-roof furnace with the swing-roof superstructure on the framework; furnace shell diameter 5 m, charge 5-45 tons. (51366)

the two last-mentioned swing-roof designs in which the furnace shell is placed in a framework on which the swing-roof column stands, it has been shown in practice that the shocks which occur when charging scrap into the furnace are damped so much on their way to the roof that they have no adverse effect on the life of the latter.

TILTING DEVICES

The tilting devices can be divided up into two main types: hydraulic devices on the one hand and motor-driven mechanical devices on the other. Hydraulic tilting is very usual both in Europe and the U.S.A. The general requirements for tilting make the hydraulic principle particularly advantageous. This is because very heavy weights are involved and low speeds and steady, even motion are required. Usually, the tilting cylinders are turned upside down so that the closed end is at the top.

When a rotatable shell is used, the lower anchoring points for the pistons which run in the tilting cylinders have to be located so far down that the upper closed ends of the cylinders do not project above the charging platform. Otherwise, the cylinders are in the way of the slag door when the shell is rotated. Particularly in the U.S.A., where there are no rotatable shells, it is usual that the cylinders are allowed to project a little way above the charging level at the sides of the slag door. Hydraulic tilting cylinders have proved to be extremely reliable. They require little maintenance, and modern methods make it possible to seal them satisfactorily.

Of the motor-driven mechanical devices, mention will only be made here of the most usual type, that is, tilting

with toothed racks. This is simple in principle, but great care must be taken to see that, for example, pieces of scrap do not get in between the teeth. A certain disadvantage is that, because of the risk of the relatively weak rack rods bending out, it is usually desirable that they should be pulled rather than pushed, for which reason the centre of gravity of the furnace must be so arranged that there could be a risk of the furnace toppling over during tilting if the rack rods happen to come loose, for example, if their foundation gives way.

CRADLES AND RAILS

The most usual practice when cradles and rails are used is that the latter are horizontal and straight (Fig. 6). In order to prevent the cradles from moving, holes can be made in the rails with corresponding projections on the cradles, or the rails can be cogged with corresponding cog segments on the cradles. The latter is not, however, as usual as the former except where curved rails and cradle have been adopted.

Generally speaking, the furnace must be tilted some 42° for tapping and up to 15° for slagging. The difficulty may then arise that the electrode masts and the superstructure can get in the way of overhead crane tracks, etc., when tilting is carried out. For this reason, curved rails with corresponding cogged segments have sometimes been introduced (Fig. 7). By selecting a suitable curvature, it is possible to lower the furnace so much during tilting that a reduction in the height of the overhead crane track of as much as 0.5 m (20 in.) can be gained. Naturally the adoption of a curved shape for the rails and the cradle means additional mechanical complications.

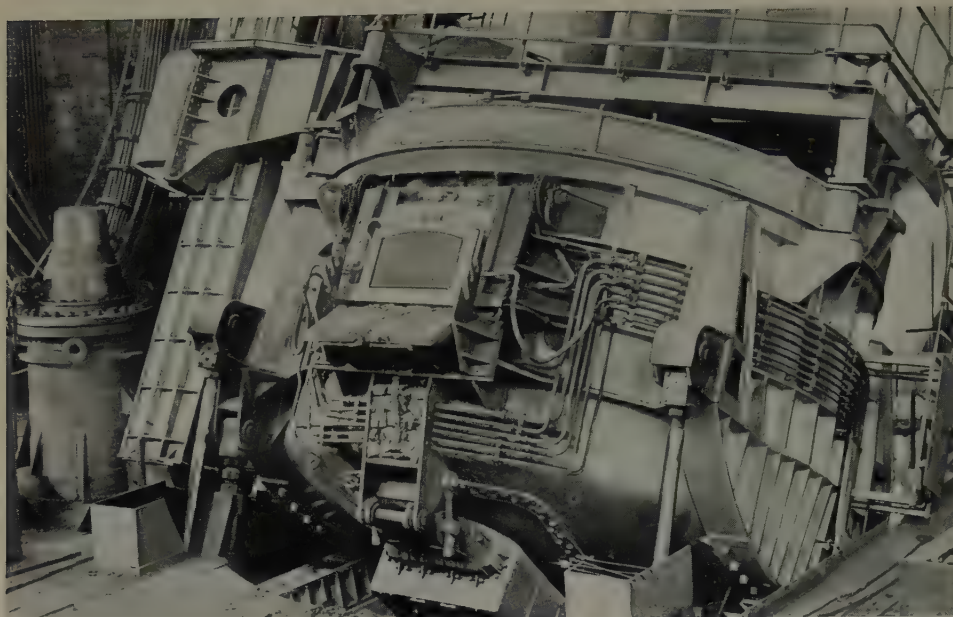


Fig. 6. Arc furnace with a shell diameter of 5 m normal cradles with straight rails. (48854)

It is important to remember that the cradles should be placed well away from the centre of the furnace so that they are situated as far out of the danger zone as possible should there be a break-through in the furnace bottom. Furnaces which are placed on a framework are particularly suited to the protection of the cradle in this way. A point which should be noted in this connection is that care should be taken to see that, when the furnace is in the horizontal position and is about to receive a charge of scrap from the charging bucket, it is mechanically supported so that the shocks caused by charging are not transmitted to the tilting devices.

THE FURNACE SHELL

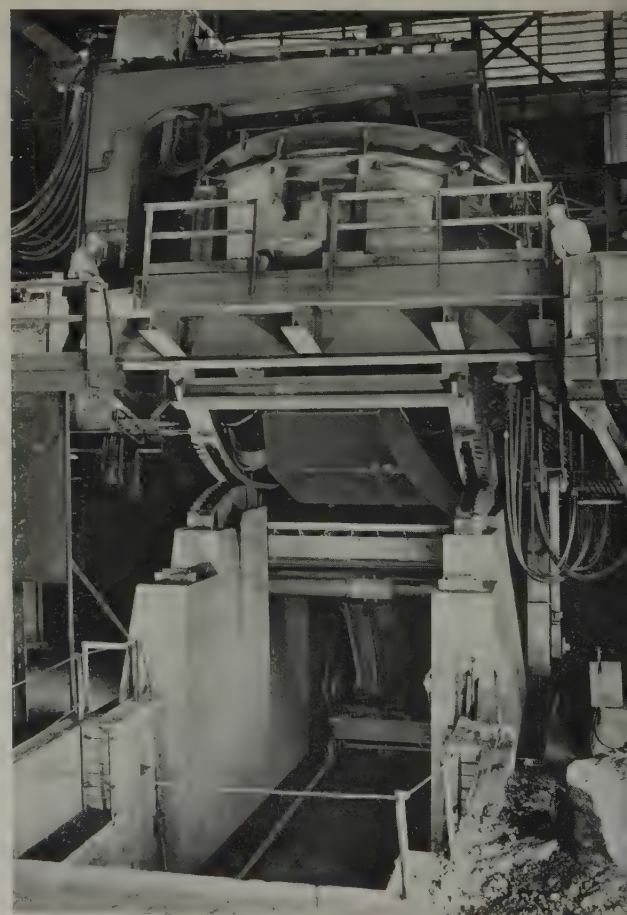
Almost without exception, modern furnaces are built with dome-shaped furnace bottoms (Fig. 8) and with vertical, cylindrical side walls. The American firm which has for a long time advocated flat furnace bottoms has recently built several furnaces with dome-shaped bottoms. The main reason for having dome-shaped bottoms is that it is not then necessary to employ any mechanical devices to reinforce and support the bottom since it then becomes a self-supporting structure.

The most striking development in the case of the furnace shell is that, in recent years, the height of the vertical furnace wall has been increased. The actual depth of bath for a certain furnace diameter has not changed very much. Only in those cases where an induction stirrer has been introduced has there been tendency to make the bath deeper. It is also of interest to note that the thickness of the lining at the bottom of the furnace has not changed very much during the years.

One of the reasons why the depth of the furnace has been increased, or to be more precise, the height of the

shell, is that the scrap now available is very much less dense than previously. The scrap now available can be expected to have a weight per unit of volume of 300–800 kg/m³ (about 20–50 lb/cu.ft) as against a previous figure of 1,200–1,500 kg/m³ (about 75–100 lb/cu.ft).

Fig. 7. A 90-ton arc furnace, furnace shell diameter 6.1 m (20 ft), cradles with coggled segments. (41600)



the case of a furnace with a diameter of 5 m (about 16 ft 6 in.), which was previously made with a height of 1.25 m (4 ft 1 in.) from the slag sill to the roof lining, in modern furnaces this dimension has been increased to 1.75 m (5 ft 9 in.). Another example is that, in the case of a furnace with a diameter of 6 m (about 20 ft), the corresponding height is now about 2 m (about 6 ft 6 in.) as against something of the order of 1.25 m (4 ft 1 in.) previously. It should be borne in mind that an increase in the height of the shell by a certain amount means an increase in the total furnace height and with it an increase of twice this amount in the height of the building.

Previously, it was most usual that the furnace shell was a riveted structure but, in recent years, welded designs have been adopted. However, care has to be taken when designing furnaces to ensure that there is no kerf effect because of the cyclic changes in temperature which occur in furnaces. It may be of interest in this connection to mention that an American furnace-building firm has introduced a furnace shell, the walls of which consist of a framework into which loose steel plates are fitted so that the furnace can "breathe".

The tendency to make modern furnaces with high vertical shell walls is an interesting example of how the question of efficiency is solved. The fact that the walls are higher means that the electrodes have to be made longer inside the furnace. This also means greater surfaces through which the heat is dissipated, that is to say, increased losses. However, it is of the greatest importance that, in swing-roof furnaces, additional charges should be reduced to a minimum, since they cause a loss of furnace time. The result is that total efficiency is increased by increasing the height, at any rate, to the extent mentioned above.

ROOF RINGS

Previously, roof rings were made with a diameter equal to, or even less than that of the furnace shell. Now it is usual to build the roof rings larger than the furnace shell so that they project beyond it. In this way the roof lining is better protected from the effect of the heat, and it has even been possible by adopting this measure to dispense with water cooling. It is normal, however, at any rate in Sweden, to cool the roof ring with water in order to prevent it from becoming distorted, and to increase the life of the refractory bricks nearest to the roof ring. It is becoming more and more usual, however, to dispense with sand seals, and to rely instead on the good fit of the surfaces around the enlarged roof ring. An interesting tendency is also that attempts are being made to build the roof rings of standard sections. The roof ring is normally suspended at four points.

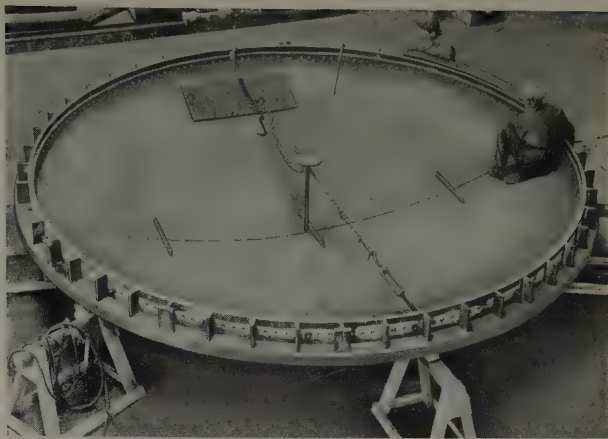
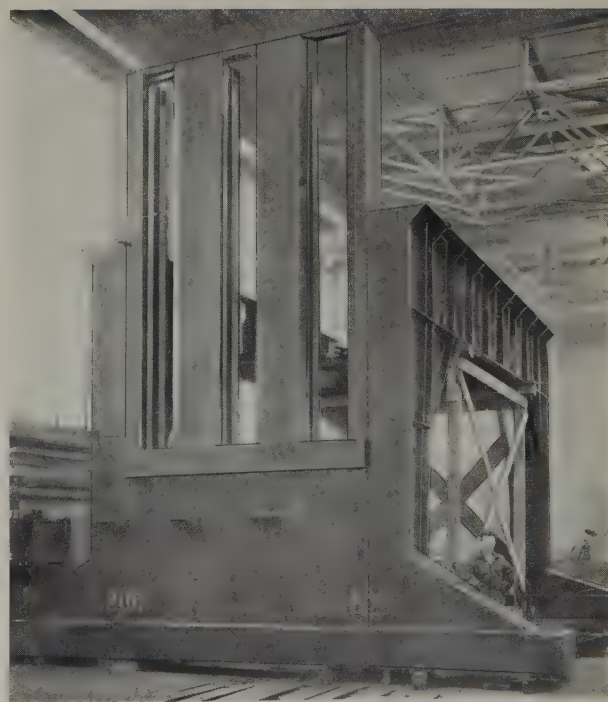


Fig. 8. The bottom of an arc furnace with a shell diameter of 5 m. (39043)

DOORS

Doors on large furnaces are almost always water-cooled and the door openings provided with cooling boxes at the sides and top. Sometimes a looped cooling tube is used for the arched roof of the slag door thus avoiding welded joints and considerably reducing the risk of leakage of the cooling water. An interesting question is whether there should be an inspection door 90° from the slag door or not. An inspection door complicates the lining of the furnace, but the most important disadvantage is that the heat losses through the doors are

Fig. 9. Electrode masts for a 5 m arc furnace during erection in the workshops; in the foreground, the tracks in which the trolleys for the electrode arms are to run. (41999)



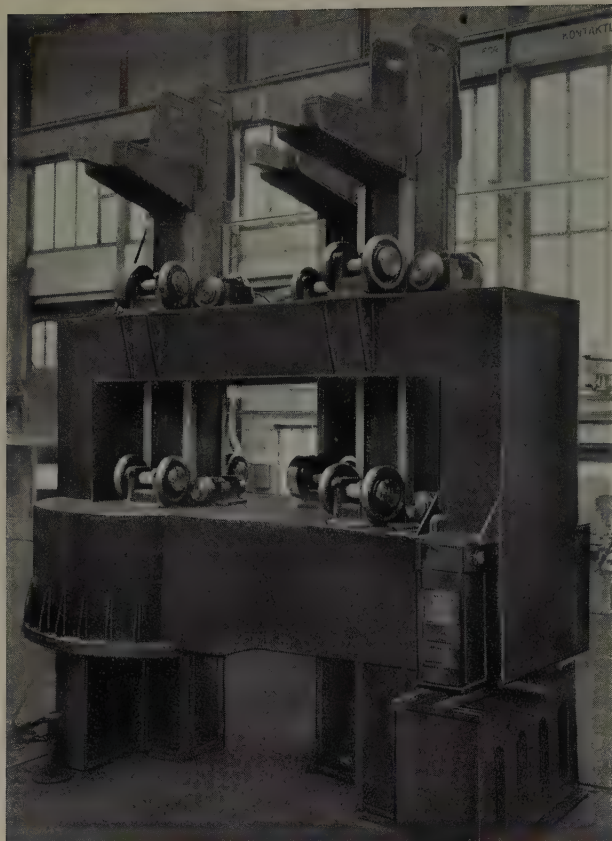


Fig. 10. Electrode masts for a 5-ton arc furnace of swing-roof type being erected in the workshops. The electrode masts are integral with the electrode arms and run against wheels which are fixed in place. (49953)

rather large. Therefore, in each individual case, it should be seriously considered whether an inspection door is really required or not. It is now possible to patch the lining by means of a spray gun. Further, for furnaces with induction stirrers, one of the main arguments in favour of an inspection door – that it can be used when de-slagging – loses significance.

ELECTRODES

There are two types of *electrode mast design*. The one has fixed vertical masts with tracks. The horizontal electrode arms can move up and down with the aid of trolleys which run on wheels in the above-mentioned tracks (Fig. 9). In the other type, the vertical masts are integral with the horizontal electrode arms (Fig. 10). The masts run up and down between guide wheels which are placed in the other structural part of the furnace.

In the case of medium-sized and small furnaces, both types are used to approximately the same extent, but in the case of large furnaces, it is the last-mentioned type with movable masts that is dominant. This is

doubtless because, when the furnace is tilted, the masts are not in their highest position and that it is then less difficult to avoid the overhead crane track.

The *electrode arms* (Fig. 11) usually consist of steel tubes or are of welded structural design. The current is taken along the arm by means of water-cooled copper tubes. Care should be taken to see that the electrical insulation between the electrode clamps and the other parts of the furnace is so far away from the electrode clamps themselves that it is protected against flames which cannot, of course, be avoided around the clamps.

During the years there has been a variety of types of *electrode clamp*, and there are still many patented clamps which are thought to have their own special advantages. However, the simple clamp with a pressure block which forces the electrode against the opposite wall of the clamp now appears to be almost alone in the field. The walls against which the block presses the electrode, are shaped so that they form two vertical seats. The block is pressed against the electrode by spring pressure and it can be released by a pneumatically or hydraulically operated piston. Usually, in order to minimise losses, the clamps are made of pure copper with cast-in cooling tubes for the water.

Electrode regulators can be electric or hydraulic. Without condemning the former type, which is well suited for use with small and medium-sized furnaces, it should be pointed out that, in the case of large furnaces, hydraulic regulators are much to be preferred since they may be said to possess virtually all the qualities required of a regulator. It is also the case that, by far the greater part of the large furnaces which have been installed on the continent of Europe in recent years have been fitted with hydraulic regulators. In the U.S.A. too there is considerable interest in using them for large furnaces.

Two disadvantages of hydraulic electrode regulation are usually quoted, that is, difficulties connected with the leakage of hydraulic fluid and the risk of freezing in a cold climate.

The first question can quite simply be dismissed because of the improvements brought about by modern sealing techniques. It must, however, be admitted that the problem of freezing has not been entirely and satisfactorily solved. Immersion heaters can be used and the hydraulic liquid circulated by pumping, the system can be drained when not in use during cold weather, and external heating, such as the blowing of hot air around the hydraulic system, can be arranged. None of these systems is without disadvantages. Naturally, the simplest method is to mix anti-freeze in with the hydraulic fluid just as is done in the case of car radiators.



Fig. 11. Electrode arms for
5-ton arc furnace.
(50025)

ELECTRICAL EQUIPMENT

A matter which is always very much discussed when designing arc furnace installations is the highest and the lowest secondary voltage of the furnace transformer. It is obvious that it is undesirable to set the maximum secondary voltage too high, bearing in mind the difficulties connected with the roof and the wall lining because of the radiation from the increased length of the arc. The lowest secondary voltage is determined by whether double-slag or single-slag steel is to be made. The regulating range of the transformer should not be made greater than is absolutely necessary since this adds considerably to the expense of the transformer.

For furnaces with diameters of up to 5 m (16-17 ft) equipped with transformers of 12-15 MVA, the strength of the roof and the walls determines the maximum voltage. In the case of larger furnaces and greater power, it is, on the other hand, the laws of electricity which determine the highest secondary voltage which has to be adopted. The reactance of the furnaces increases in step with their size and power. It is quite simply a question of having an adequately high secondary voltage in order to force an adequate current through this reactance and the resistance in the arc.

It is common knowledge that, for a certain furnace installation working at a certain voltage level, there is a current value which gives the optimum of melting power in the arc. It is quite uneconomic to set the current higher than this value, and that is the criterion against which the maximum secondary voltage must be measured. In the case of a 30 MVA transformer the most suitable secondary voltage is one of about 500 V. If the voltage is below this level, the peak of the efficiency curve is passed. It should be mentioned that the above refers to a frequency of 50 c/s. When a comparison is made with the secondary voltages in use in the U.S.A., it should be

borne in mind that 60 c/s is the normal frequency there. Therefore, all the reactances there are 20 per cent greater, for which reason a voltage of 600 V would be required in the case mentioned above.

Investigations of the conditions during practical service with a large number of furnaces have shown that, when making double-slag steel, a minimum power of about 100 kW/m² (about 9 kW/sq.ft) of bath surface is required, and for single-slag steel, approximately twice as much. If, in the case of a large furnace, a calculation is made to find out the size of the bath surface and consequently the amount of power required at the lowest voltage tapping, it is a simple matter to work out the voltage required at that level. In the case of transformers of the order of size of 30-35 MVA, it has proved that about 100 kW/m² (about 9 kW/sq.ft) gives a minimum secondary voltage of 150-200 V. It simply does not pay to have a voltage below this value.

It may be of interest to mention that it is by no means impossible to reduce reactance in large furnaces. In Germany, a large furnace has been built with the transformer built into the swinging superstructure of the furnace, thus ensuring very much shorter secondary cables and in this way reducing the reactance. However, a great deal can be said against making a component as vital as the transformer movable. Experience with this furnace has not yet made it possible to say whether this method has any future.

There is, however, another way which is extremely interesting even though it does not entirely solve the problem, and that is the use of a series capacitor for the compensation of the high reactance. This is used in electric reduction furnaces, for example, Tysland-Hole furnaces for the smelting of pig-iron, with great success. So far, series capacitors have not been used with arc

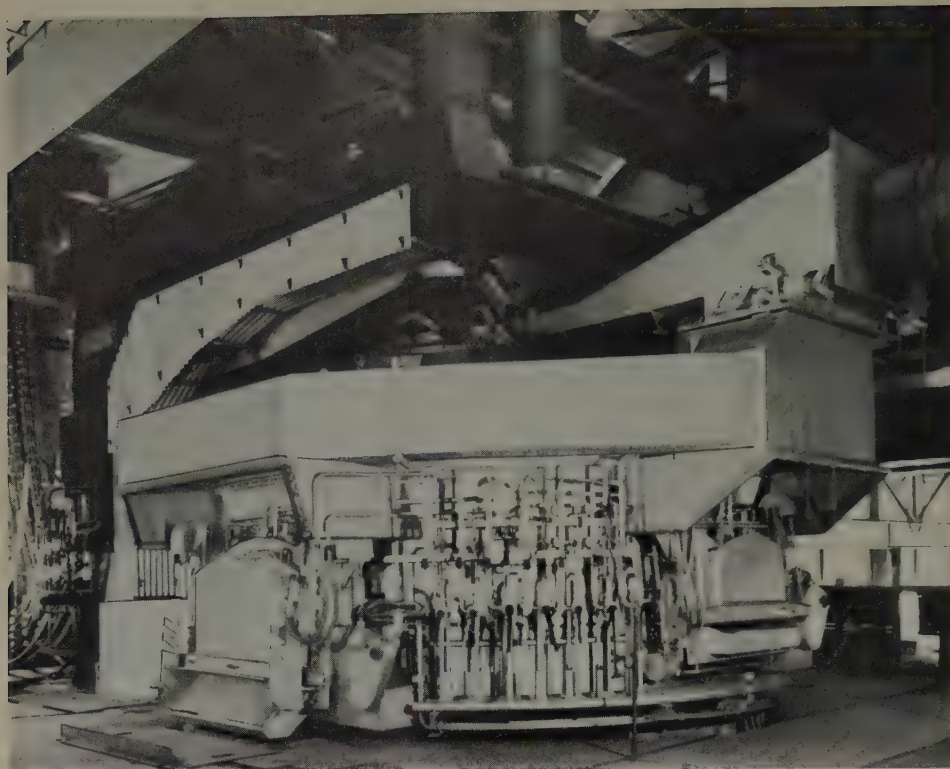


Fig. 12. Arc furnace, shell diameter 5 m. The furnace is provided with fume extraction equipment. (52443)

furnaces. Instead, reactance has been added in order to reduce the stresses on the feeding networks, but the time to adopt this new measure may now be at hand. In the case of these large furnaces, the series capacitor fulfils the task of providing a better power factor for the feeding network, and reduces the size of the furnace transformer.

FUME EXTRACTION

A problem which has come very much to the fore in recent years is fume extraction. Usual practice is to let the gases from the arc furnaces find their own way up towards the roof of the steelworks and from there out into the open air. As more and more buildings are built around the steelworks, however, it is quite clear that something must be done to deal with the problem of fumes. The requirements calling for more satisfactory air conditions in the works themselves are becoming stricter too.

The blowing of oxygen into the furnaces, which is becoming more and more usual, causes a very great problem in this connection because of the large quantities of gas involved. If blowing with oxygen is not adopted, it is not too difficult to arrange fume hoods over the doors and around the electrodes (Fig. 12). When there are larger quantities of gas it is, as mentioned above, much more difficult. In several places an attempt has been made to

solve the problem by placing one large hood high above the entire furnace. This hood has sides which hang down around the top of the furnace.

In some places, especially in the U.S.A., extraction tubes have been built either into the roof or into the sides of the furnace shell, for example, at the inspection door. However, large tube dimensions – 1–2 m (about 3 ft – 6 ft) diameter – are required.

Naturally, the gas which is extracted from the furnace has a considerable amount of solid particles in it; figures of 2–15 kg/ton (about 4–30 lb/ton) of steel produced in the furnace are sometimes quoted. Thus, the gas must be cleaned in a suitable way and, in many cases, too, its heat content should be utilised.

The major problem connected with the fumes is the design of the extraction devices close to the furnace. It is extremely difficult to make them so simple that the operation of the furnace is not disturbed. If extraction is effective, the pressure in the furnace may be several tenths of a mm water column less than in the atmosphere outside (1 mm water column = a pressure of about 0.0015 lb/sq.in.). This is not much but there is a risk that so much air will be drawn in that, in many cases, undesirable oxidation of the slag will take place. The cleaning of the gases and the recovery of their heat contents cannot be said to present any major problems to the steelworks, since there are many well-tested methods to be selected from, but the installations are expensive

AUTOMATIC DEPTH CONTROL OF SUBMARINES

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Asea Reg. 62

general description of the Asea system of automatic depth control of submarines. The function and construction of the system are dealt with in detail, and in conclusion some examples are given of operational results.

The need for automatic depth control of submarines has grown with the introduction of the "snorkel" and nuclear power propulsion machinery.

A theoretical approach to the problem has been published earlier [1]. In Sweden a corresponding theoretical treatment of the submarine dynamics has also been carried out. In contrast to this, Asea has made an approach based on experimental data. This has resulted in an automatic control system, which in 1960 has been in use for about nine years. The design is based on frequency-response curves [2], characterising the effect of

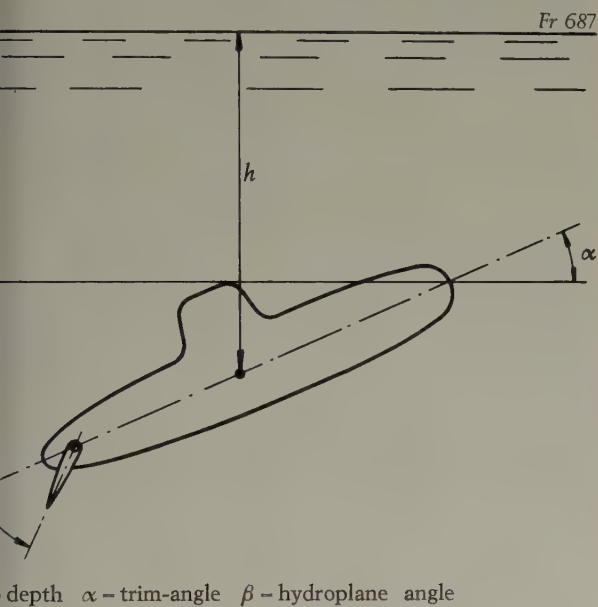


Fig. 1. The submarine in underwater position.

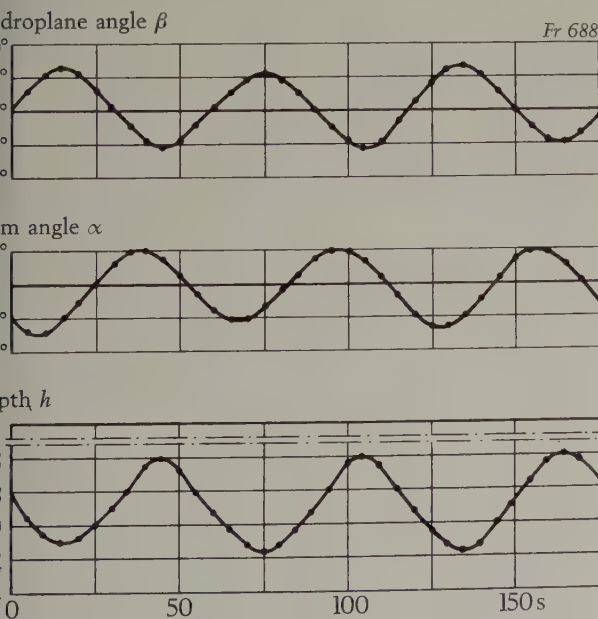


Fig. 2. Recording of frequency analysis test $\omega = 0.105$

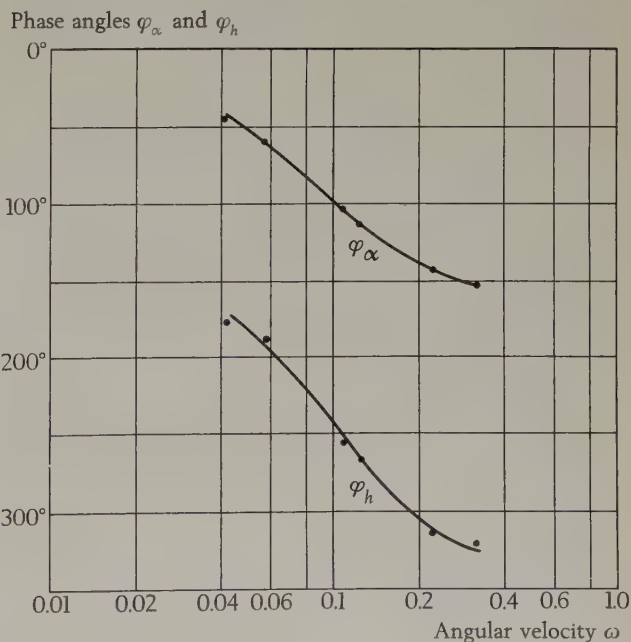
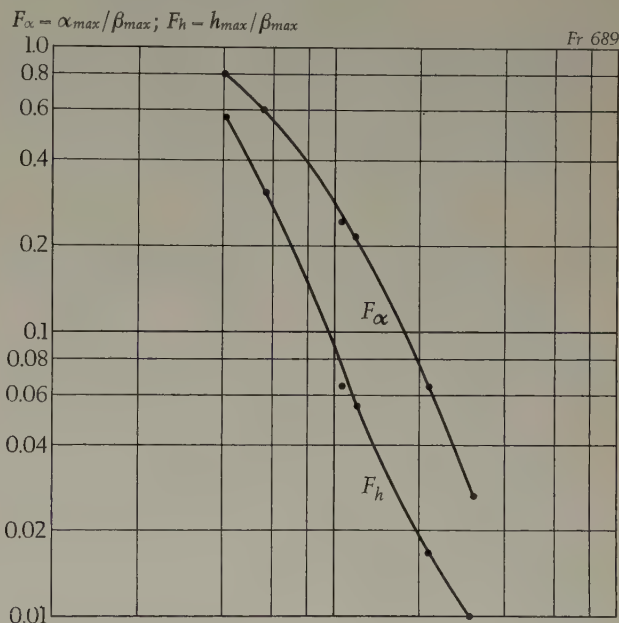
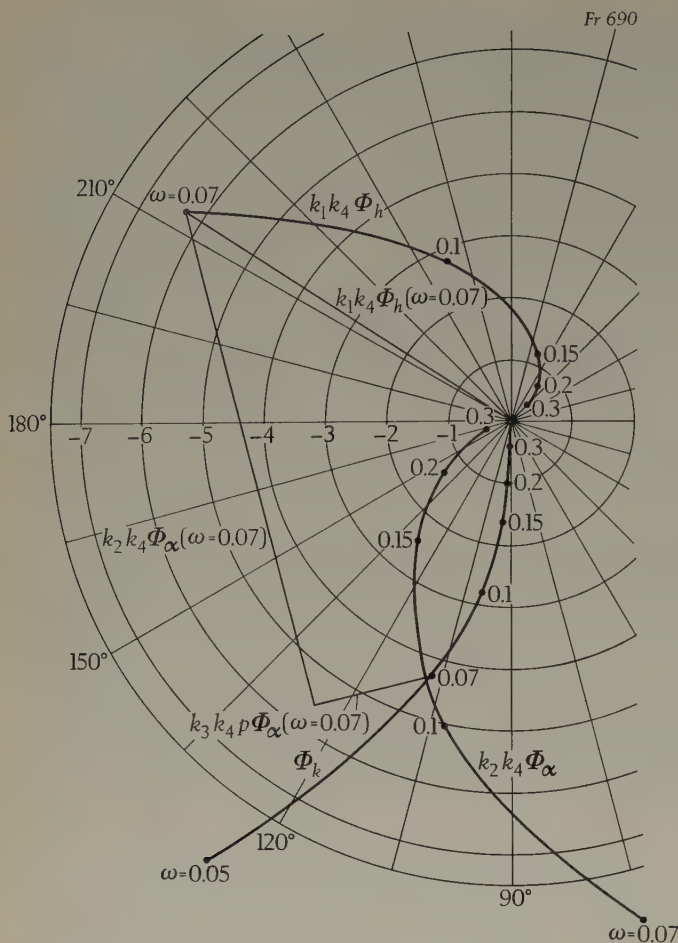


Fig. 3. Frequency-response diagram.



Φ_h – frequency response function for the depth
 Φ_α – frequency response function for the trim-angle
 Φ_k – frequency response function for the open control loop
 k_1 – k_4 – amplification factors, see Fig. 5

Fig. 4. Nyquist diagram for the control system.

the control hydroplanes on the hull of the submarine. These curves were recorded in a submarine which was kindly placed at our disposal by the Swedish Naval Administration.

EXPERIMENTAL FREQUENCY-ANALYSIS INVESTIGATION OF THE SUBMARINE

The measuring of the frequency-response for the submarine was carried out in the following way. The control hydroplanes were moved up and down sinusoidally as a function of time, and the submarine moved consequently in a practically sinusoidal track in the vertical plane. The depth, the trim-angle and the hydroplane angle were recorded simultaneously. The test was carried out at different speeds, different frequencies and different amplitudes of the hydroplane angle.

Fig. 1 shows the hull of the submarine and the three recorded quantities, the depth h , the trim-angle α and the hydroplane angle β . A typical recording is shown in Fig. 2.

From these recordings it is possible to calculate the frequency-response functions Φ_α and Φ_h for the trim angle α and the variations of the depth h , dependent on the hydroplane angle β

$$\Phi_\alpha = F_\alpha / \varphi_\alpha$$

$$\Phi_h = F_h / \varphi_h$$

where $F_\alpha = \alpha_{max} / \beta_{max}$ and $F_h = h_{max} / \beta_{max}$ and φ_α and φ_h are the phase angles between the complex functions and α , and β and h , respectively. The frequency-response diagram at a given submarine speed is shown in Fig. 3 and the corresponding Nyquist diagram in Fig. 4.

THE AUTOMATIC CONTROL SYSTEM

The frequency-response curves for the submarine enable us to study the stability and the response for different control systems. An exact investigation may be carried out in an analogue computer, but it is also possible to treat the problem approximately by means of the Nyquist diagrams and estimate the behaviour of suitable control systems [2].

The control system is principally based on the controlled value h and its first and second time derivatives dh/dt and d^2h/dt^2 . If the vessel is moving with constant speed in the direction of its longitudinal axis, α and dh/dt are identical for small values of α , and therefore in practice there is little to choose between either of the following systems:

1. The signal for the hydroplane control system is composed of the components h , dh/dt and $d\alpha/dt$
2. The signal is composed of h , α and $d\alpha/dt$

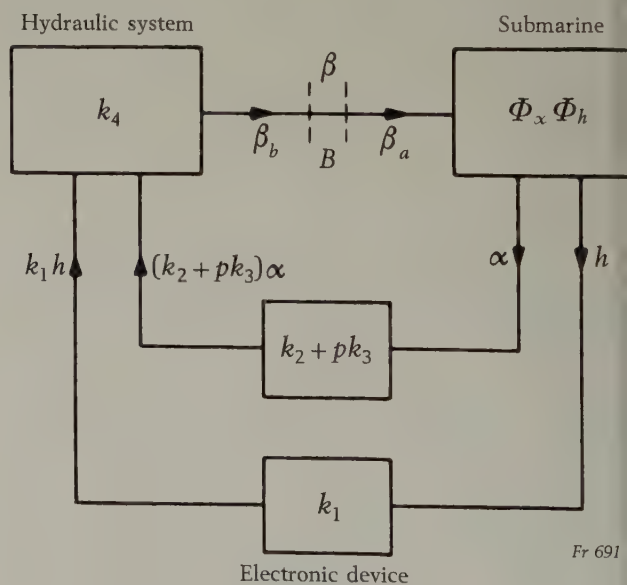


Fig. 5. Block diagram for the control system.

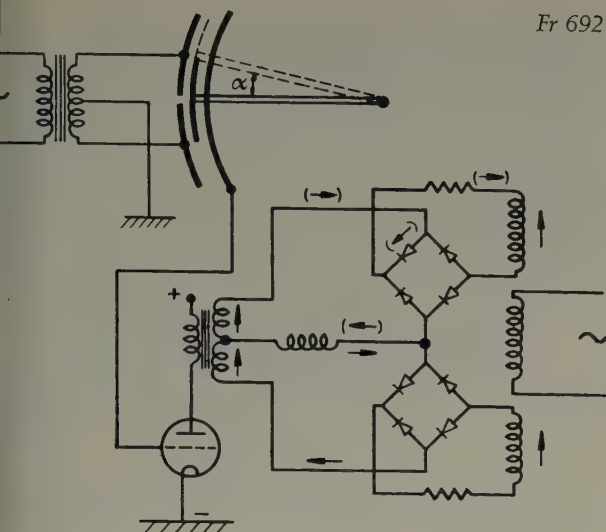


Fig. 6. Differential capacitor transducer.

Since the frequency of oscillation for the movement of the hull of the submarine is very low, we may assume with fair accuracy that the control system is "ideal", that is, the hydroplane angle moves proportionally to the control signal without delay. We shall later see how this is attained.

System 1 is theoretically more advantageous than system 2 because the control signal in this case does not contain the component α , and the controlled value h is thus not influenced by the trim-angle. Nevertheless, we have chosen system 2, because the component α is physically easier to derive than the component dh/dt , and the influence of the trim-angle on the controlled depth, which might have been a practical drawback, proved to be negligible.

The block diagram for system 2 is shown in Fig. 5, where the amplification factors k_1 , k_2 , k_3 and k_4 for the electronic device and the hydraulic system are real coefficients. With the annotations given in the figure the following control equations are obtained [2]

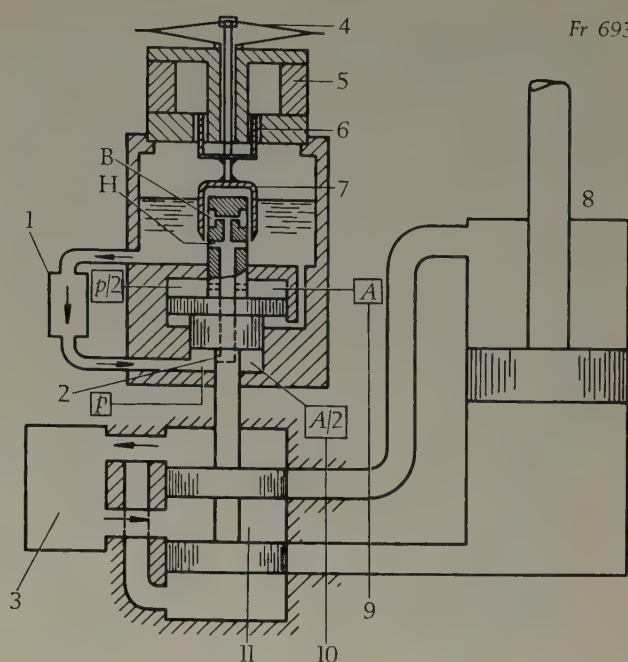
$$\Phi_\alpha = \Phi_\alpha \quad (3)$$

$$\Phi_h = \Phi_h \quad (4)$$

$$\Phi_h = k_1 k_4 h + (k_2 + p k_3) k_4 \alpha \quad (5)$$

If we open the control system at the point B, we obtain the following transfer function for the open loop

$$\frac{\beta_b}{\beta_a} = k_1 k_4 \Phi_h + (k_2 + p k_3) k_4 \Phi_\alpha \quad (6)$$



- | | |
|-------------------|-------------------|
| 1. Oil pump | 7. Pilot ring |
| 2. Pin hole | 8. Servomotor |
| 3. Oil pump | 9. Upper chamber |
| 4. Spring | 10. Lower chamber |
| 5. Magnet | 11. Main valve |
| 6. Regulator coil | |

Fig. 6. Differential capacitor transducer.

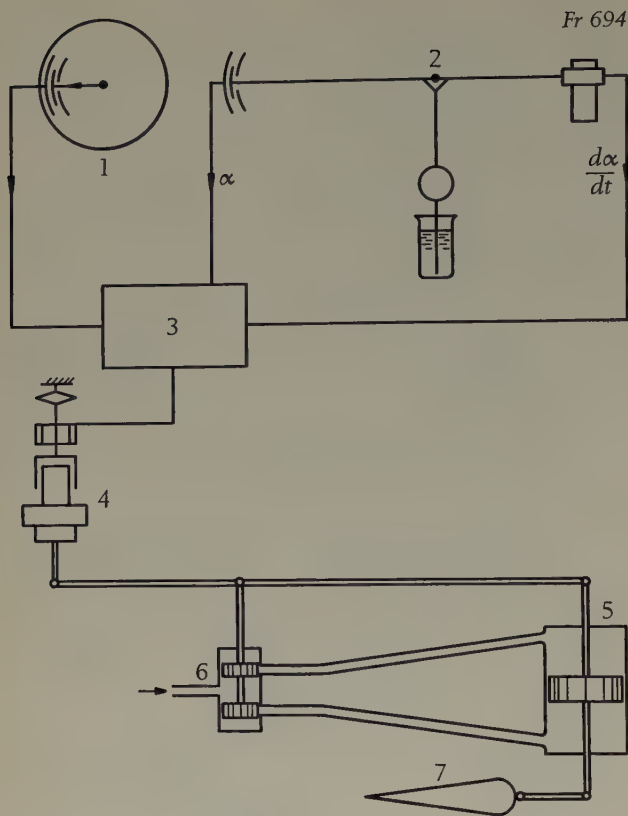
Fig. 4 shows how the frequency response curve Φ_k for the open control loop is constructed as the sum of its three components $k_1 k_4 \Phi_h + k_2 k_4 \Phi_\alpha + k_3 k_4 p \Phi_\alpha$. The constants k_1 , k_2 , k_3 and k_4 are chosen in such a way, that the Φ_k -curve passes the point -1 with a phase-margin, which ensures good stability for the control system.

DEDUCTION OF THE CONTROL SIGNALS

The depth h is measured by a manometer, and the position of the pointer is converted into an electrical signal by means of a differential capacitor. In this way no additional load is applied to the meter. The principle of the system is shown in Fig. 6 and is described in earlier papers [3, 4].

The trim-angle α is measured by an oil-damped pendulum fitted with a similar capacitor device. The pendulum also carries a coil, moving in the air-gap of a loudspeaker magnet. In this coil a voltage is induced proportional to $d\alpha/dt$.

The three control signals are summed in an electronic amplifier, where the coefficients k_1 , k_2 and k_3 can be preset to suitable values.



1. Depth meter
2. Trim angle meter
3. Electronic device
4. Electrohydraulic regulator
5. Servomotor
6. Main valve
7. Hydroplane

Fig. 8. Elementary diagram for the control system.

THE ELEMENTARY DIAGRAM FOR THE CONTROL SYSTEM

The output signal from the amplifier is intended to operate the hydroplanes in such a way that the hydroplane angle β is proportional to the signal. This may be attained in different ways, but a suitable device is an electro-hydraulic regulator, which, in combination with a hydraulic servo-motor, operates the hydroplanes.

The principle of the electro-hydraulic regulator is shown in Fig. 7, and a special feature is the hydraulic balancing of the pilot ring, which eliminates all friction [5]. The time-delay of this regulator is so small that it has no practical influence on the response of the system.

The complete control system is illustrated in Fig. 8. By means of the links between the servo-motor, the main valve and the electro-hydraulic regulator, the servo-motor is bound to follow the movement of the regulator. The same result is obtained if the hydroplane angle β is fed into the amplifier, giving the output signal

$$s = -\beta + k_1 k_4 h + (k_2 + p k_3) k_4 \alpha \quad (7)$$

In this case, no mechanical connection between the servo-motor and the main valve is needed.

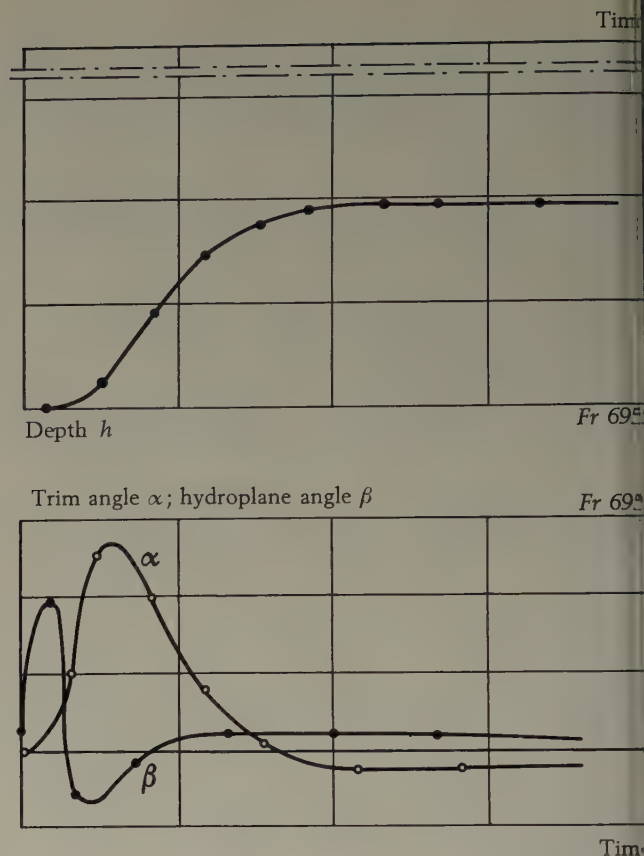


Fig. 9. Recording of transient response to an alteration of the depth setting.

OPERATIONAL RESULTS

Fig. 9 shows how the depth h , the trim-angle α and the hydroplane angle β vary as functions of time when the depth setting is suddenly altered by 2 metres. It appears from the recording that the response is aperiodically damped, and that the hydroplanes have returned to zero and made a deviation in the opposite direction before any alteration in the depth can be seen. This is

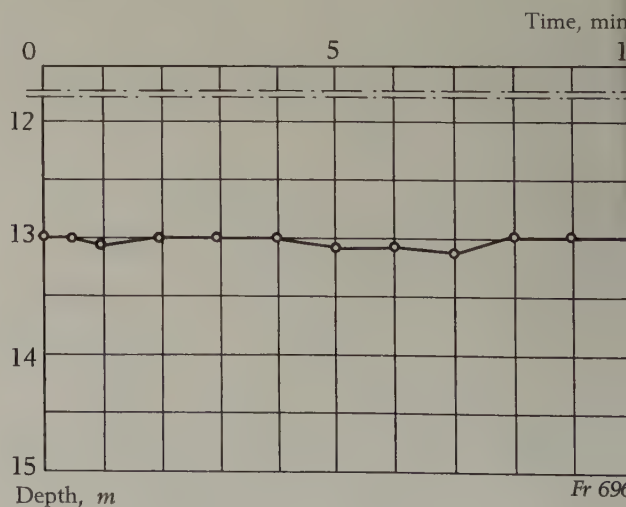


Fig. 10. Controlled depth by constant depth setting.

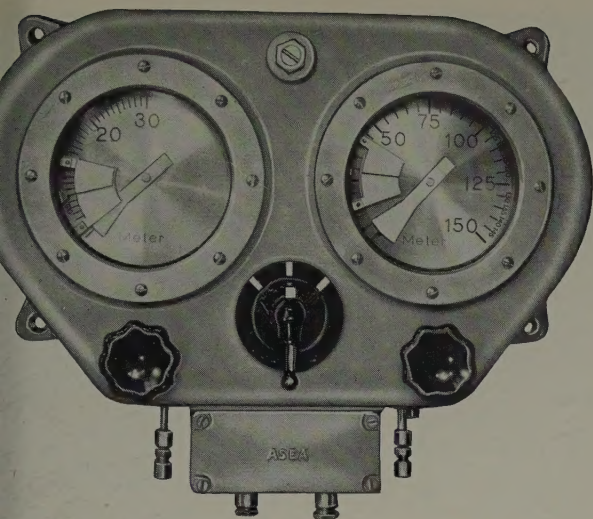


Fig. 11. Depth meter. (Z 7273)

naturally a result of the control signal being composed of the components h , α and $d\alpha/dt$. The corresponding coefficients k_1 , k_2 and k_3 thus give at this speed an ideal transfer response, and normally the same coefficients may be used for all speeds of the submarine.

Fig. 10 shows a recording of the depth using automatic depth control with constant depth setting.

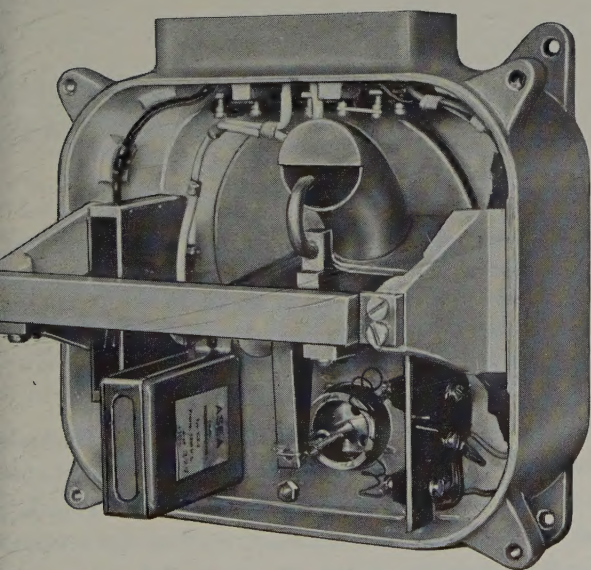


Fig. 12. Trim-angle meter. (Z 7276)

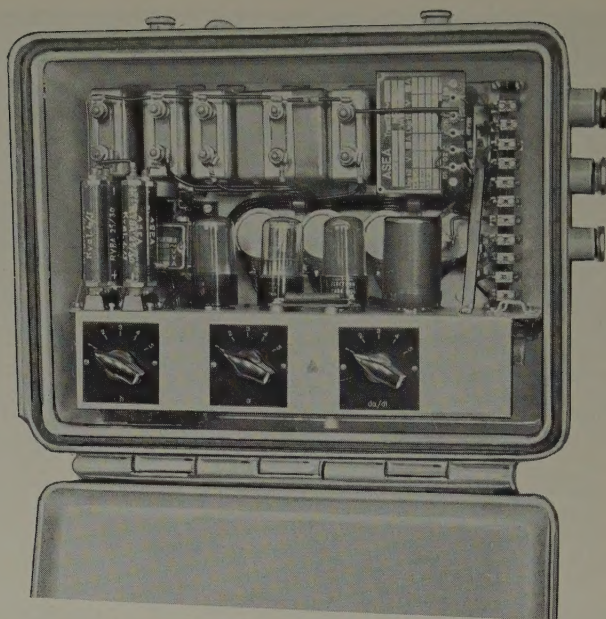


Fig. 13. Electronic amplifier. (Z 7210)

DESIGN

The four components of the system are shown in Figs. 11–14. The depth meter, Fig. 11, has two manometers for different depth ranges, and the differential capacitor transducers are shown. On the trim-meter, Fig. 12, the damping device, the coil for $d\alpha/dt$ and the capacitor system may be seen. The electronic amplifier is shown

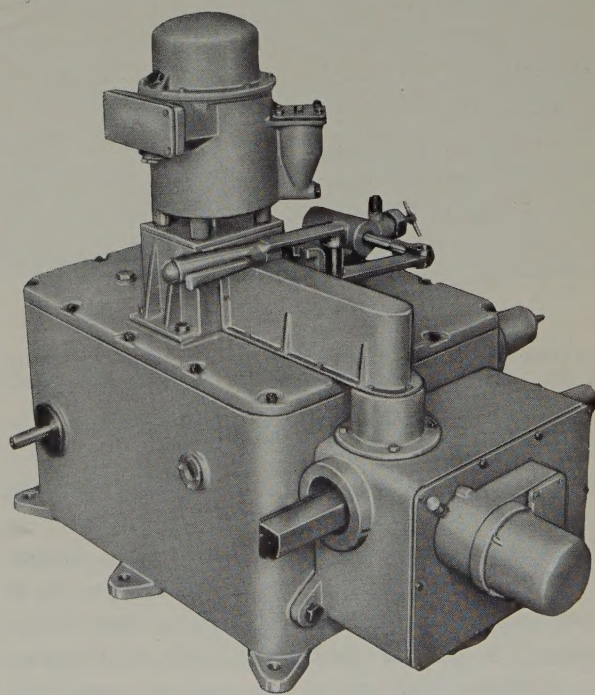


Fig. 14. Electro-hydraulic control device. (Z 7266)

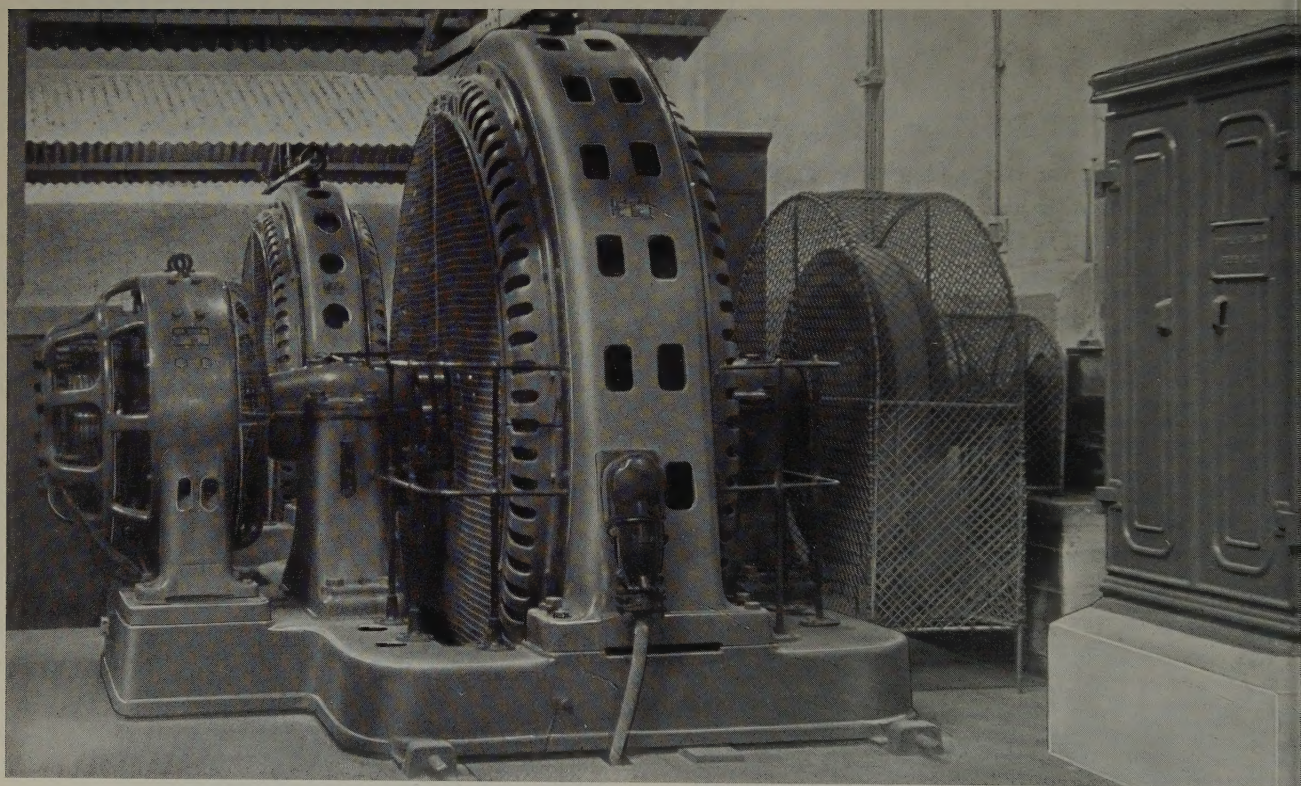
in Fig. 13, and Fig. 14 shows the electro-hydraulic device for controlling the hydroplane servo-motor.

On account of the robust and simple design of the system, a large number of equipments has been working for years without any operational failures.

On the basis of the experiences gained with the frequency-analysis tests on the first submarine it has also been possible to design the control system for other types of submarine without the need for performing tests on board ship. The optimal setting of the constants k_1 , k_2 and k_3 can be easily determined during the trials of the submarine.

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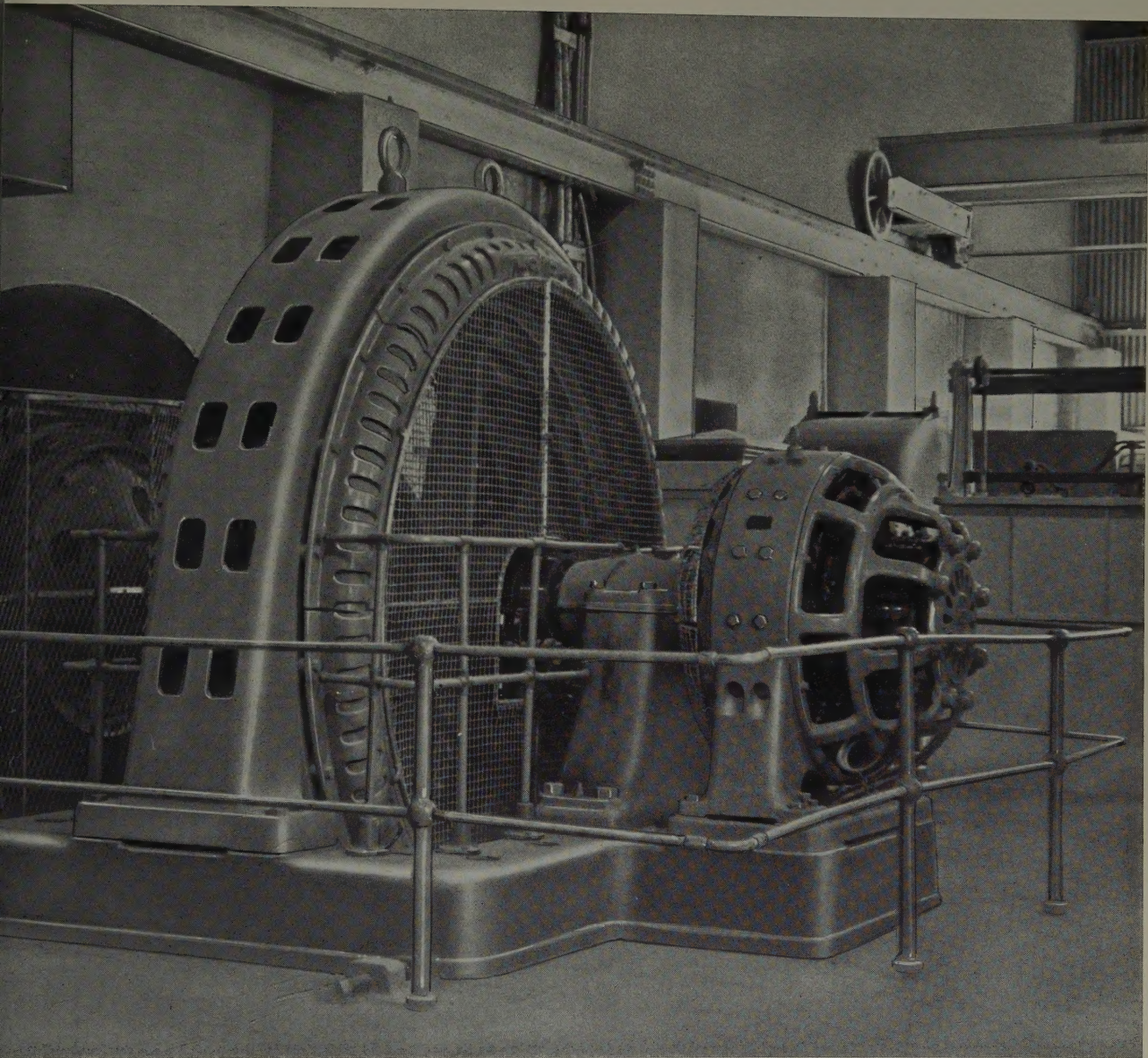
VETERAN ASEA MOTORS IN BRITISH CEMENT WORKS

Asea Reg. 442, 846

The Aberthaw and Bristol Channel Portland Cement Co. Ltd., a public company owning cement works at Aberthaw and Rhose in Glamorganshire, South Wales, and manufacturing several kinds of Portland cement, has sixteen veteran Asea motors of various sizes installed in its premises. Some of these are spares, but most are in constant use.

Two Asea synchronous induction motors driving wet-mills at the Aberthaw and Bristol Channel Portland Cement Company's works at Rhose, South Wales. In the foreground, a 450 h.p., 167 r/m motor installed in 1927; in the background, a 500 h.p., 200 r/m motor installed in 1923. (55067)

By far the greater part of these machines was installed between 1913 and 1923. There are seven motors, rated at 75 h.p., 725 r/m, 50 c/s, 3,000-3,300 V, which are used for driving kilns, secondary crushers and a waggon-haulage conveyor. There are also nine heavier motors, of both induction, and synchronous induction, type, seven of which are rated at 350, 450 or 500 h.p.

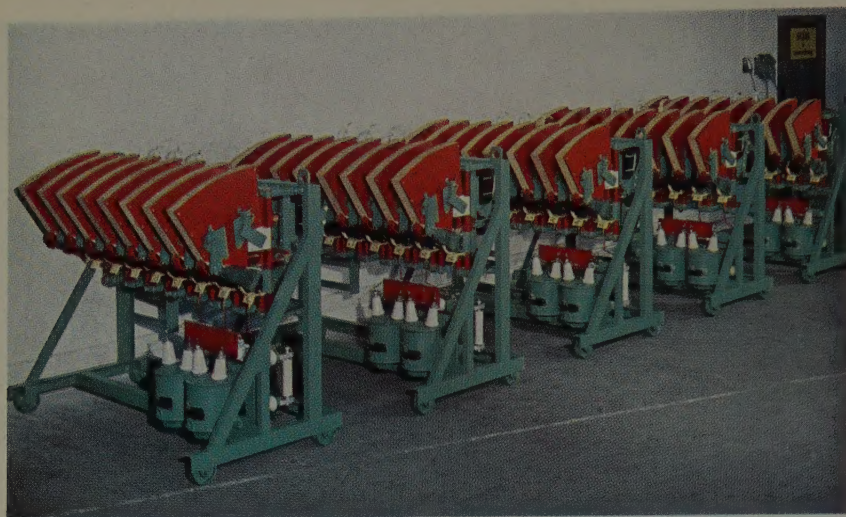


An Asea 450 h.p., 167 r/m, 50 c/s, 3,000 V, 78 A synchronous induction motor installed at the Aberthaw and Bristol Channel Portland Cement Company's works at Aberthaw, South Wales, in 1922. The motor, which has a secondary voltage of 1,000 V on starting, is fitted with an exciter rated at 2.2 kW, 32 V, 505 A, and is used for driving a wet-mill grinding blue lias limestone to slurry. (54890)

These latter are used for driving wet-mills, primary limestone crushers and induced-draught fans. They are provided with Asea starters and control equipment.

Most of these motors have to work continuously in a damp climate and, in spite of dust-collection equipment, some of them also have to operate in dusty conditions. Notwithstanding these exacting circumstances and the heavy nature of the work, the machines have been giving satisfactory service for many decades. These Asea motors count for about a tenth of the motor horsepower

developed in the two works, and several are employed in the heaviest and most vital sectors of production. A great advantage of the 450 h.p. wet-mill motors is that because of their low speed – 167 r/m – no reduction gearing is required, thus simplifying the entire drive for the grinding machinery. Further, since they are synchronous induction motors, they can be started under full load using the minimum amount of current. Once started, they run as synchronous machines with d.c. excitation, thus improving the power factor of the plant. These properties are of particular value to a company which has operated its own power-station for many years, as well as taking power from the grid. These wet-mill motors are run twenty-four hours a day for long periods, with relatively short and infrequent breaks for maintenance, and are still working well, even after many years of heavy-duty service.



(F 517)

NEWS IN BRIEF

CONTACTORS FOR 6 kV

Asea manufacture two-pole and three-pole d.c. operated contactors for a rated current of 200 A and a rated voltage of 6 kV. The illustration shows a set of contactor units for operating mine hoists. Each truck contains two mechanically and electrically interlocked reversing contactors and a two-pole contactor for d.c. breaking as well as voltage-transformers for "potential interlocking". The object of the latter is to prevent the closing of the one reversing contactor until the arc in the other has been deionised. The contactor, which has the type designation EHLA 306/200, has been put through comprehensive type tests, among which the following may be mentioned.

Breaking tests

Fifty consecutive closing and opening operations with an interval of time of 15–30 seconds at 1,200 A, 6.6 kV, P.F. – 0.4, 50 c/s. The duration of the arc was less than 30 ms.

Contact welding tests

One hundred closing operations with intervals of 15–30 seconds at 2,000 A, P.F. – 0.4. The wiping movement of the contacts was reduced in order to correspond to completely worn contacts. No sign of welding could be observed.

Contact wear tests

This test was carried out at 50 c/s, 6.35 kV, 300 A, P.F. – 0.37 and 180 opening and closing operations were carried out each hour. In all, 100,000 opening and closing operations were made at a three-phase power of 3,300 kVA, after which time the wear observed on the contacts was only half that permitted.

The contactor has been supplied for the operation of slip-ring motors with a rating of 3,000 h.p.

Asea Reg. 5356

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